Quarkonium Production in PHENIX

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PHENIX Collaboration

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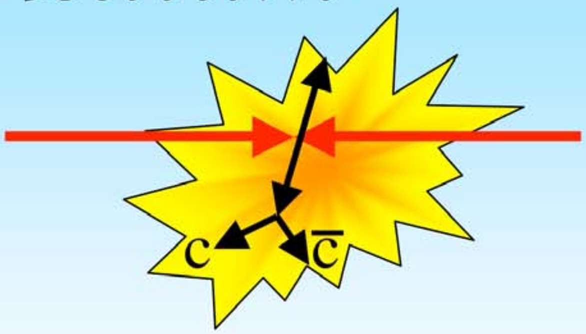
Quarkonia in the Medium

- Quarkonia Production -

  hard scattering processes result in the production of heavy quark pairs that interact with the collision medium



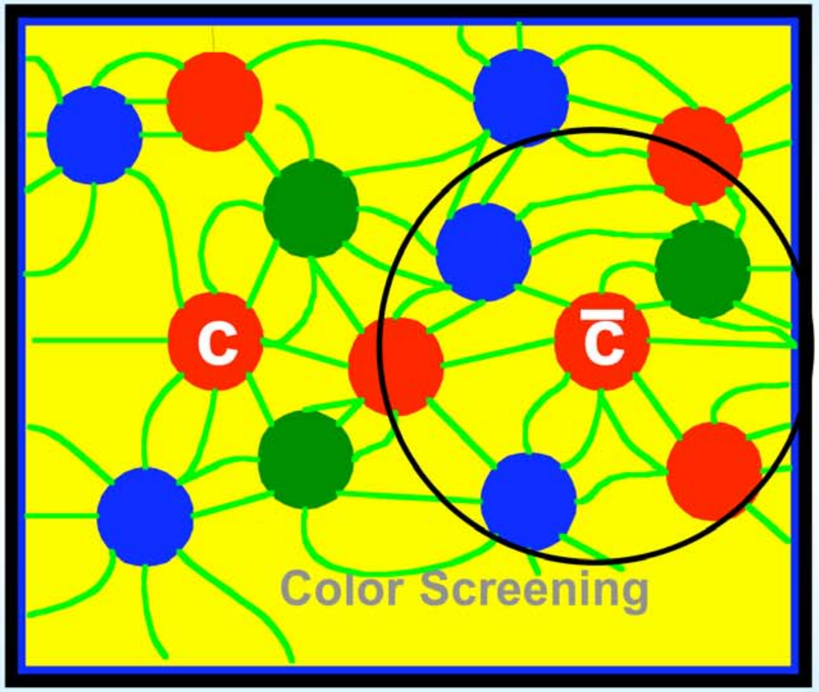
- In medium interactions convey information about the fundamental properties of the medium itself

- Competing effects are predicted to govern J/ψ production
  - J/ψ color screening:
    - Suppression of J/ψ yield with increasing collision centrality
  - J/ψ recombination:
    - Increased J/ψ yield with increasing collision centrality
    - Narrowed J/ψ rapidity and p_T distributions with increasing centrality
  - Shadowing, Heavy quark energy loss, Normal nuclear absorption, etc

J/ψ Suppression Mechanism

- Suppression Models:
  - Heavy quarkonia are formed only during the initial hard nucleon-nucleon collisions
  - Subsequent interactions only result in additional loss of yield

- Color Screening:
  - Color charge of one quark masked by the surrounding quarks
  - Prevents cc-bar binding in the interaction region
  - Characterized by the Debye screening radius (r_D)
  - If the screening radius is smaller than the J/ψ radius then the quarks are effectively masked from one another

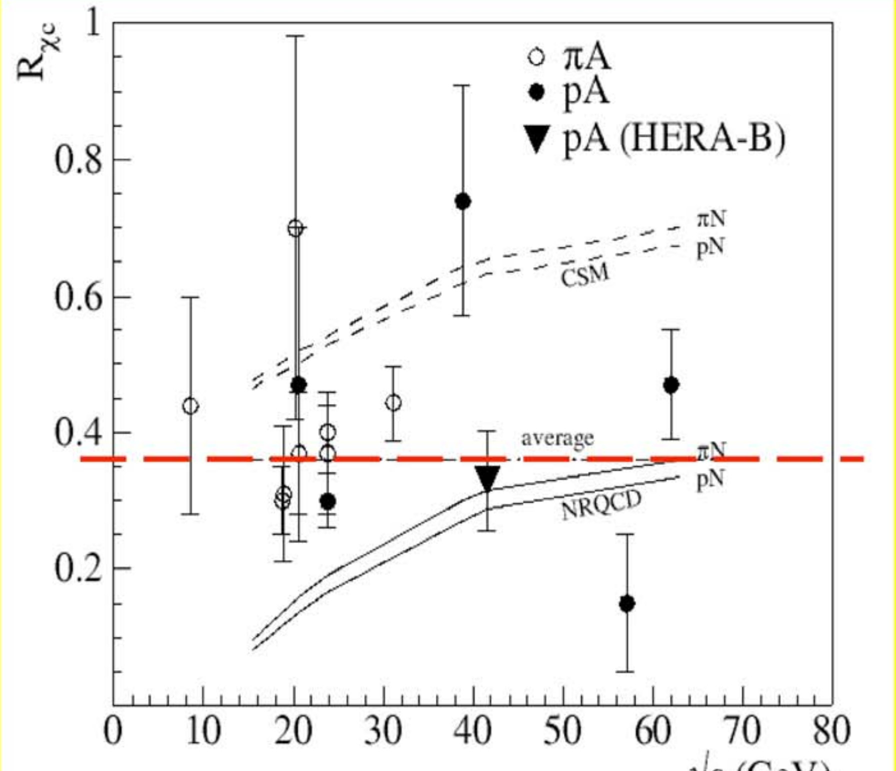


J/ψ Feeddown Effect

- J/ψ yield is populated from both direct production and feeddown from the higher resonance states
- Relative yield from each source experimentally found:
  - 60% direct production
  - 30% χ_c feeddown
  - 10% ψ' feeddown
- Medium conditions determine whether each state exists in the bound form

$$R(\chi_c) = \frac{N_{\chi_c} * (A\varepsilon_{J/\psi} / A\varepsilon_{\chi_c})}{N_{J/\psi} * \varepsilon_{\gamma}}$$

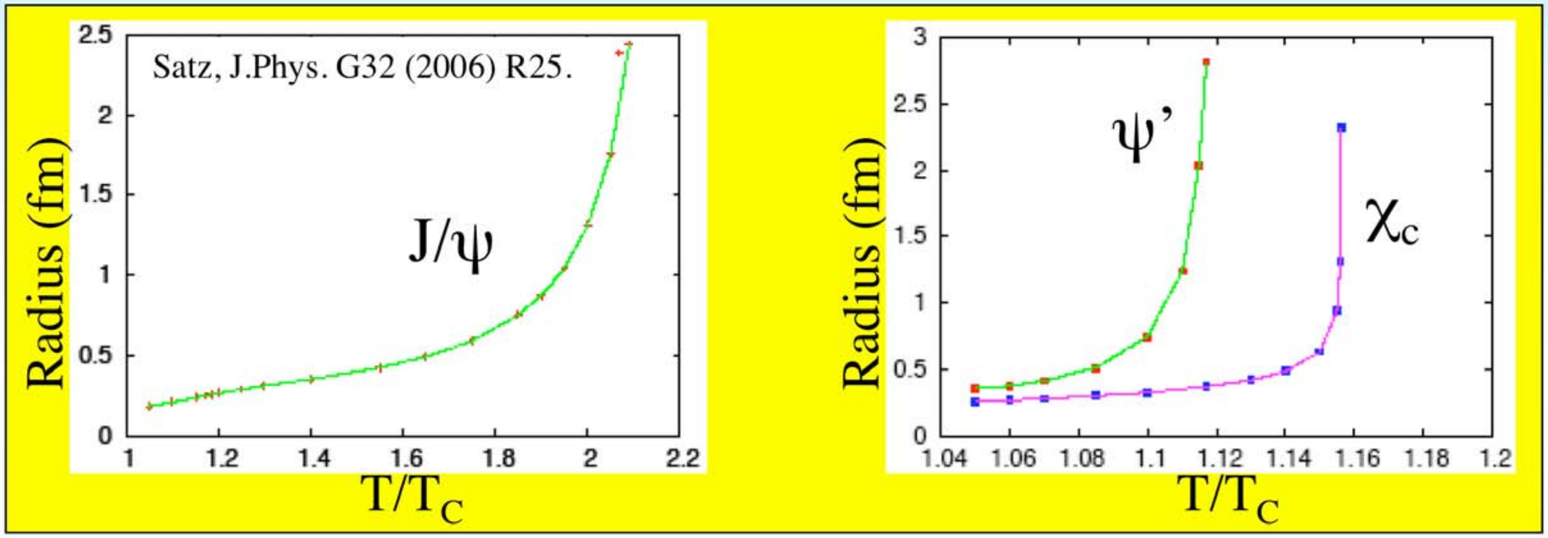
$$R(\chi_c) = 0.32 \pm 0.06 \pm 0.04$$



Phys.Lett. B561 (2003) 61-72

Sequential Charmonium Dissociation

Each state ceases to exist in the medium when the binding forces become smaller than the radius of the state



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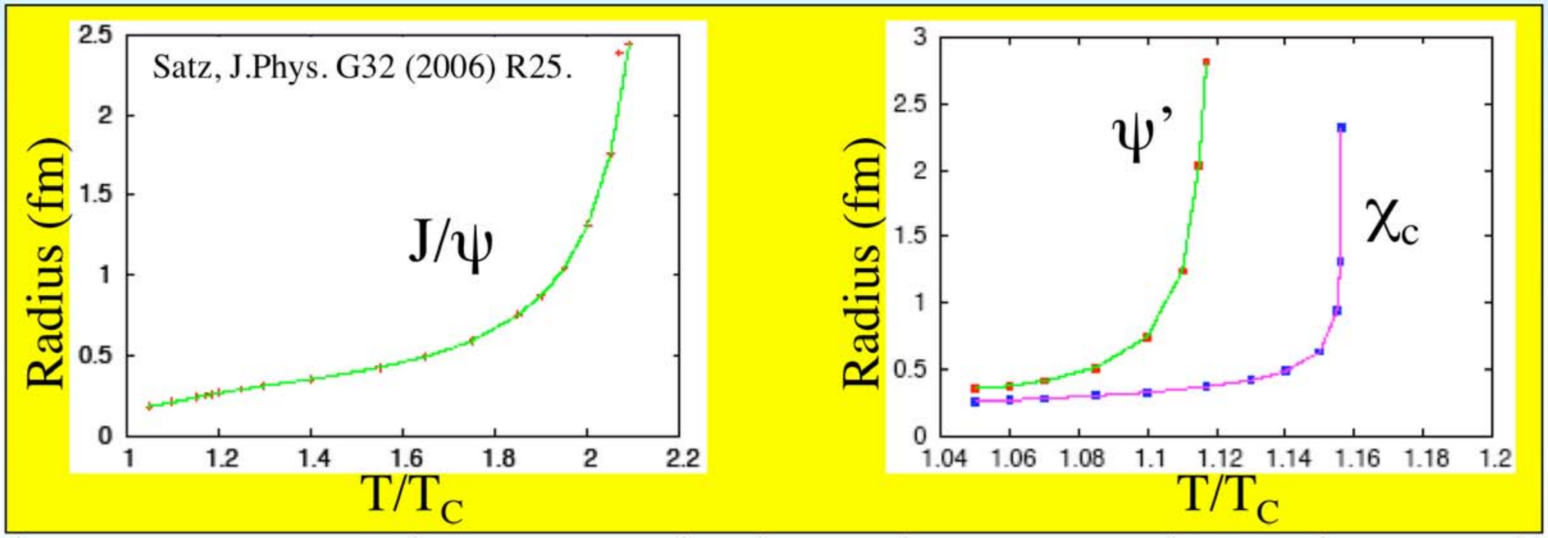
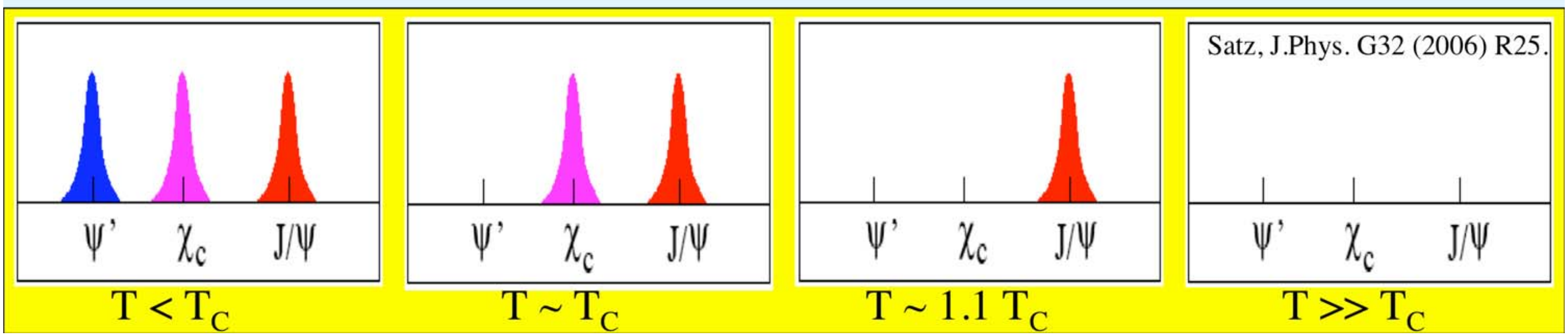
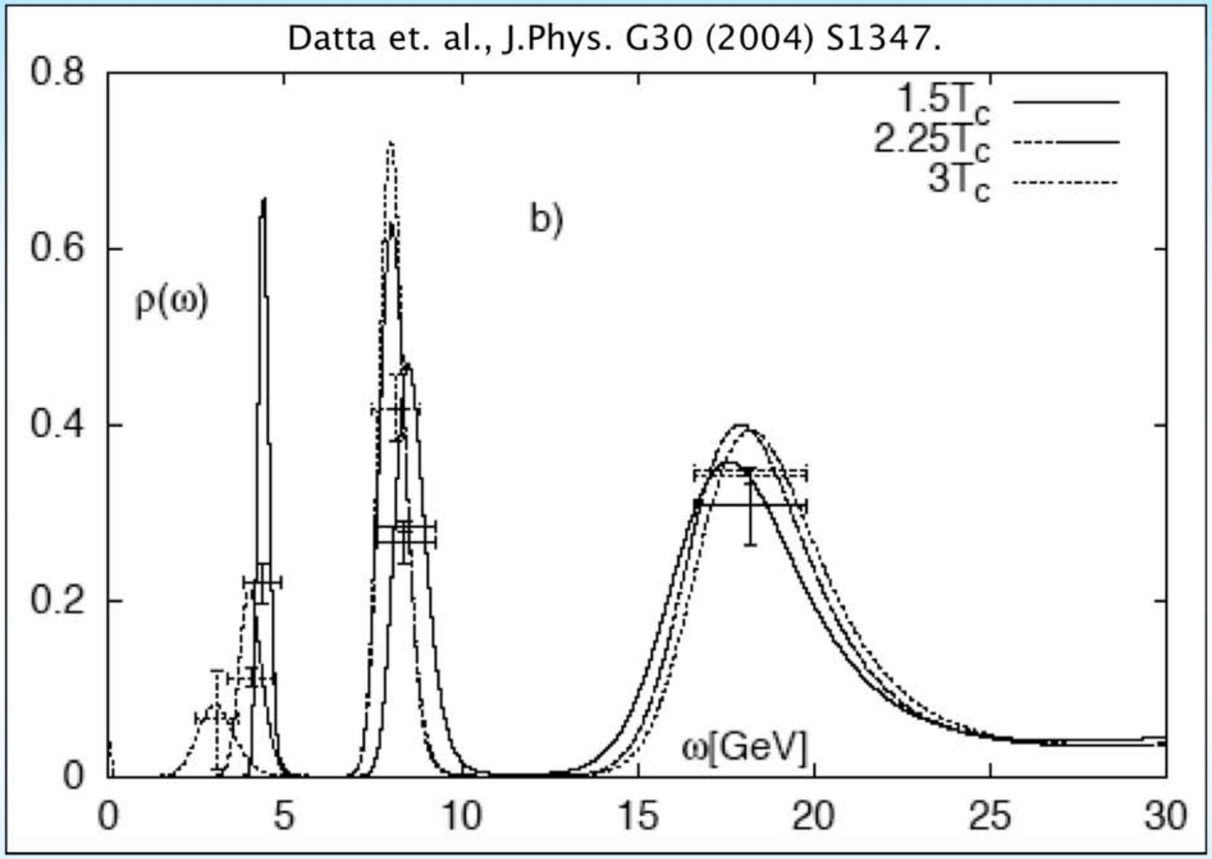


As the temperature increases the bound states melt ∴ charmonium states can serve as a thermodynamic probe of the medium

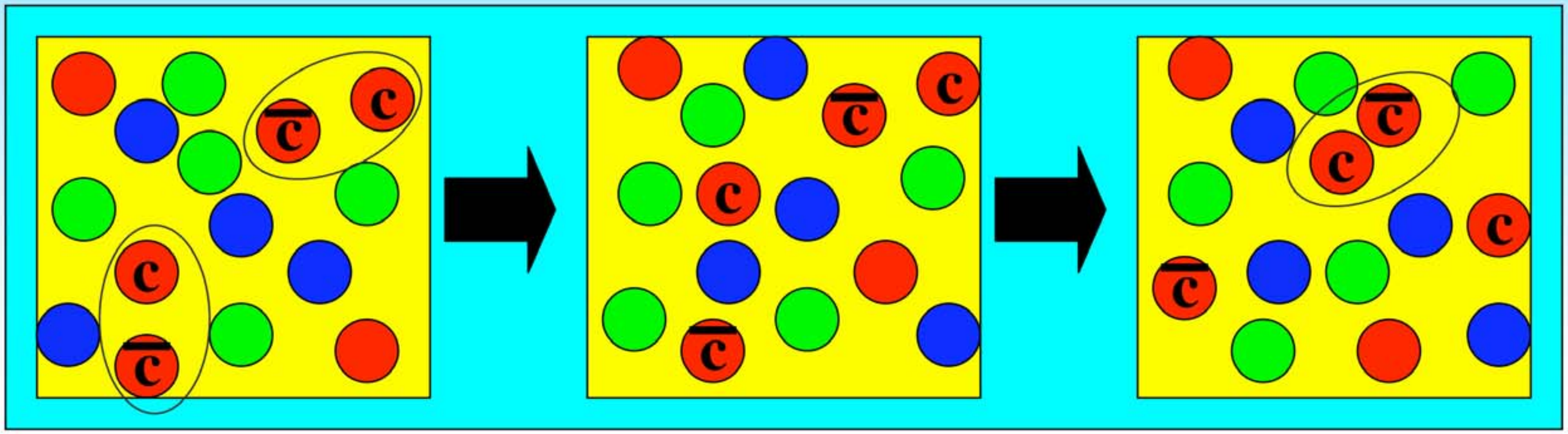


Recent Lattice Calculations



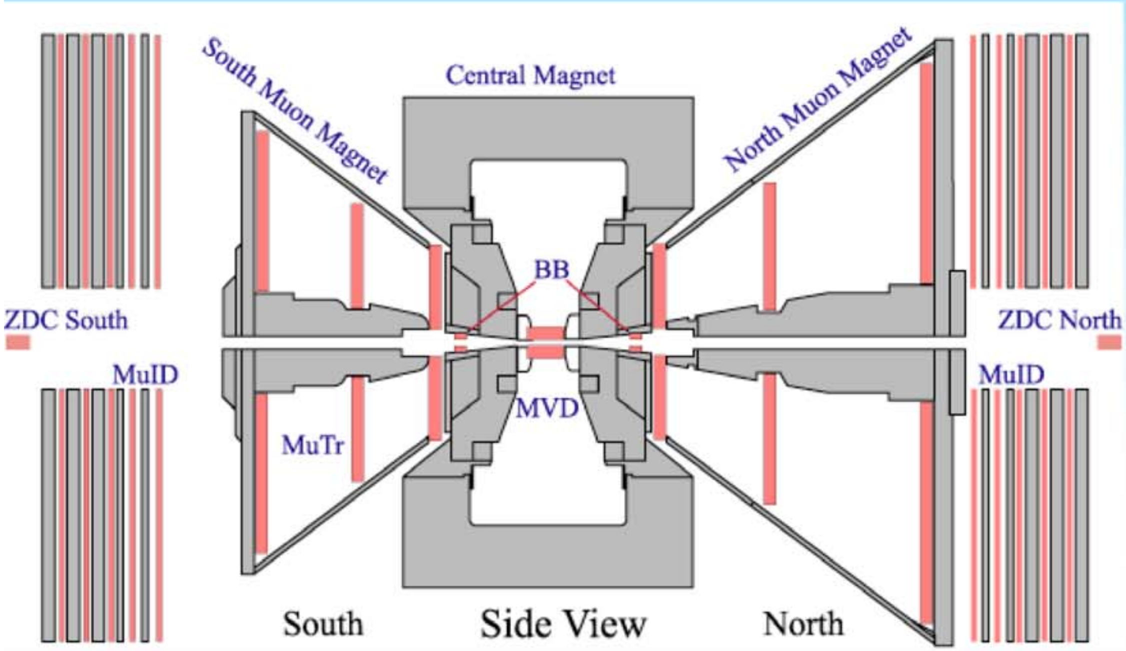
- Temperature dependence of screening radius shows no strong transition at T_c
- No significant reduction in J/ψ mass or peak strength observed up to 1.5 T_c
- J/ψ suppression may not turn on until $T > 2\ T_c$

Recombination Mechanism



- Recombination Models: $c + \bar{c} \leftrightarrow J/\psi + g$
  - In central heavy ion collisions more than one c-cbar pair is formed
    - RHIC: 10-40
    - LHC: 100-200
  - Regeneration of J/ψ pairs possible from independently produced c and cbars
  - Leads to an enhancement of J/ψ yield (or less dramatic suppression)
  - Results in modified rapidity and p_T spectra
- Comments:
  - On what time scale does this process occur?
  - What is a reasonable path length to assume the quarks traverse to recombine?

PHENIX Detector: Muon Arms

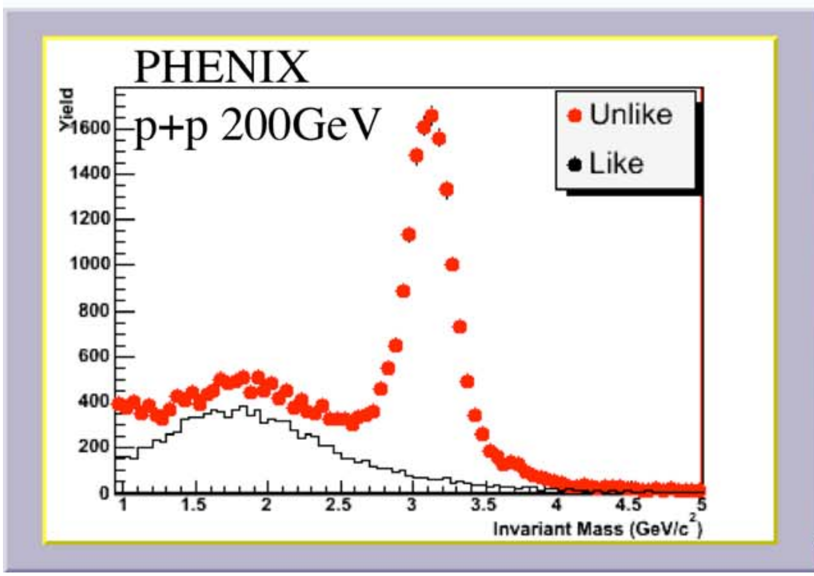


$J/\psi \rightarrow \mu^+ \mu^-$

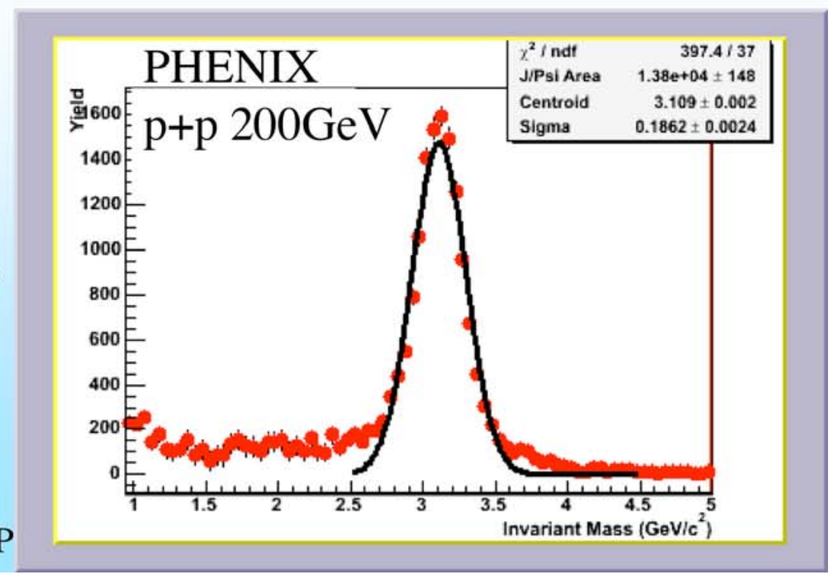
$p > 2\text{GeV}/c$

$1.2 < |y| < 2.2$

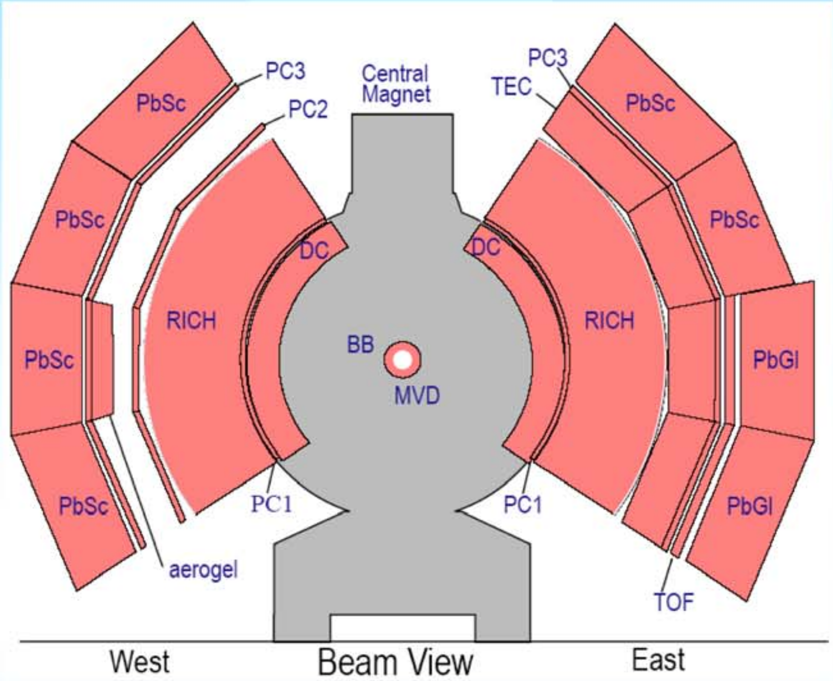
$\Delta\phi = 2\pi$



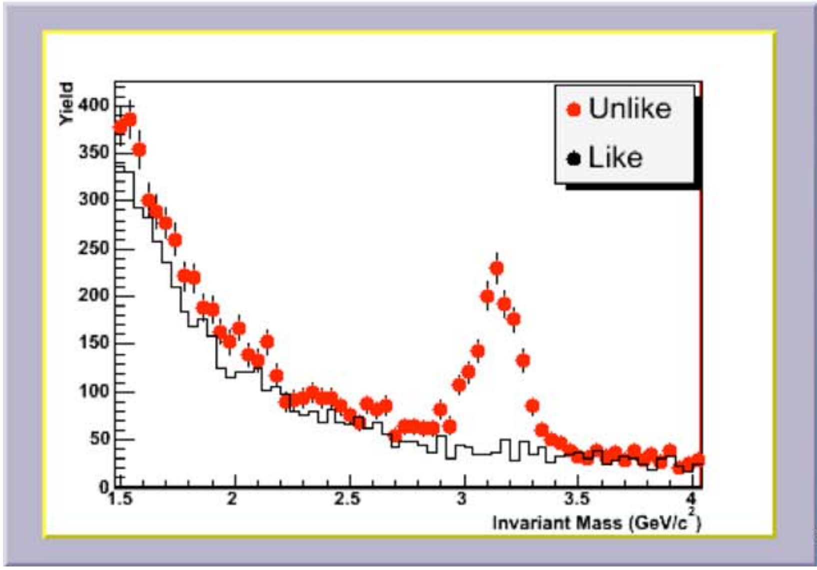
Like Sign Subtraction



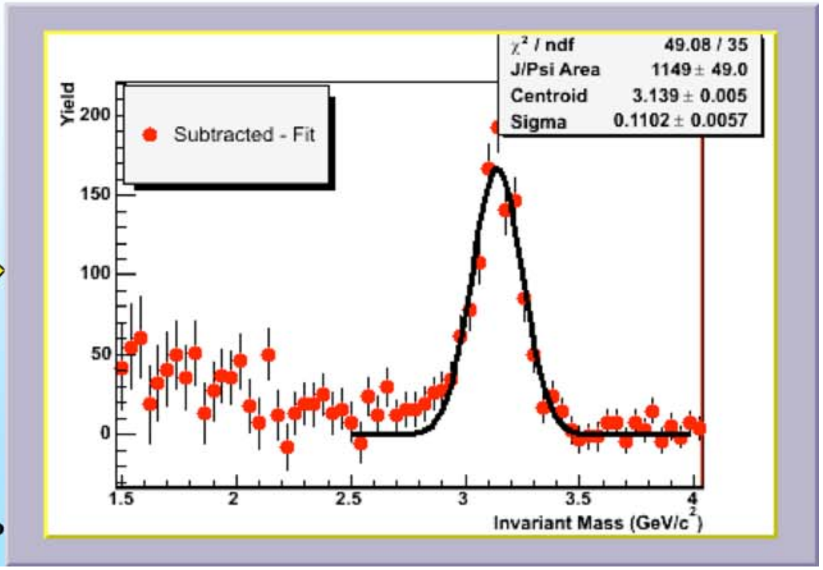
PHENIX Detector: Central Arm



$J/\psi \rightarrow e^+ e^-$
$p > 0.2 GeV/c$
$|\eta| < 0.35$
$\Delta\phi = \pi$



Like Sign Subtraction



PHENIX Data Compendium

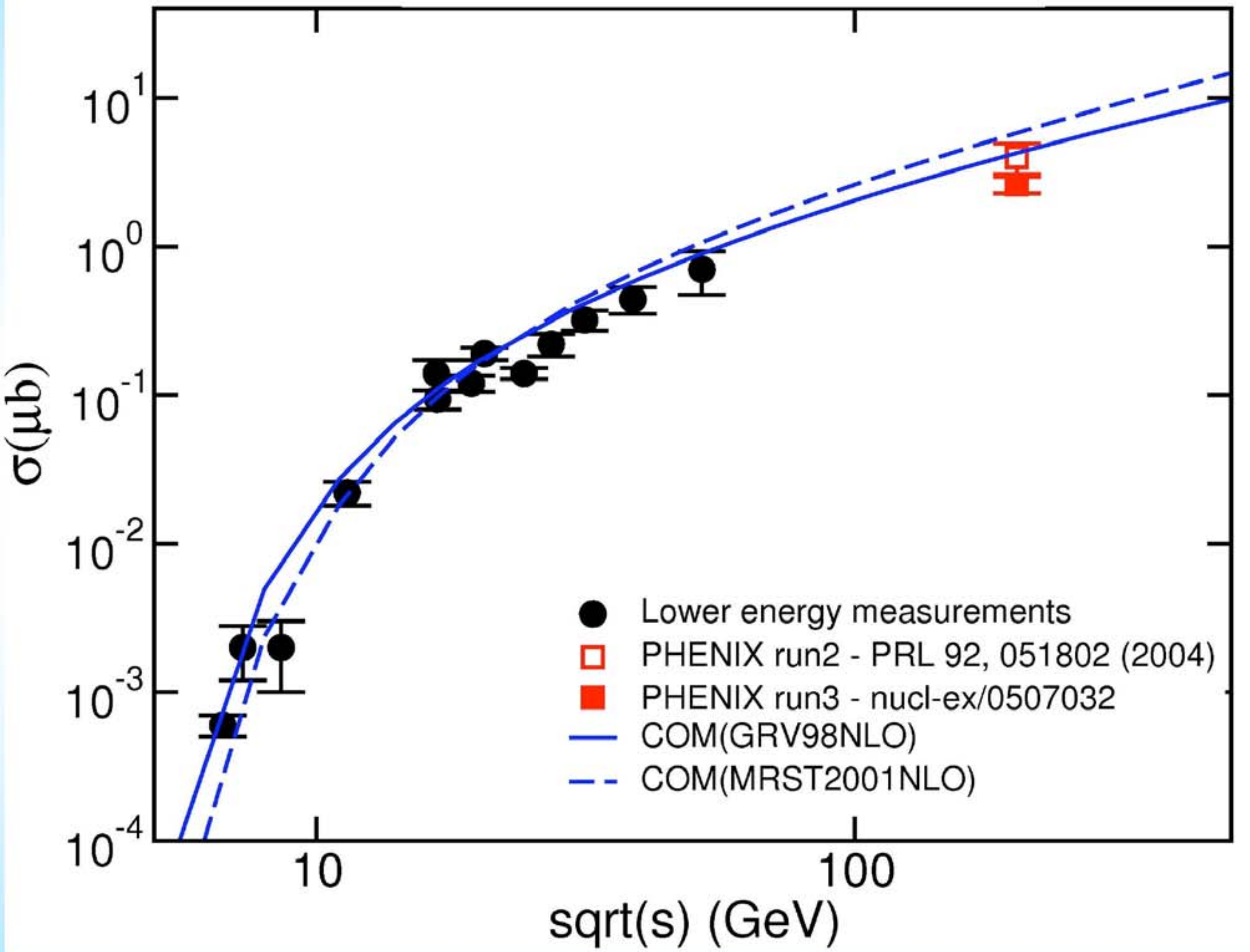
Run	Species	$s^{1/2}$ [GeV]	∫Ldt	# J/ψ $\lvert\eta\rvert<0.35$	# J/ ψ $1.2<\lvert y\rvert<2.2$
01	Au+Au	130	1 μb^{-1}		
02	Au+Au	200	24 μb^{-1}	13	
	p+p	200	0.15 pb^{-1}	46	66
03	d+Au	200	2.74 nb^{-1}	264	1656
	p+p	200	0.35 pb^{-1}	130	448
04	Au+Au	200	241 μb^{-1}	578	5168
	Au+Au	62	9 μb^{-1}		
05	Cu+Cu	200	3 nb^{-1}	542	10215
	Cu+Cu	62	0.19 nb^{-1}		146
	Cu+Cu	22.5	2.7 μb^{-1}		
	p+p	200	3.8 pb^{-1}		
06	p+p	200	10.7 pb^{-1}		
	p+p	62	?		

Reference System - p+p

- Provides baseline measurement to which all other collision systems can be compared

J/ψ Cross Section vs Energy

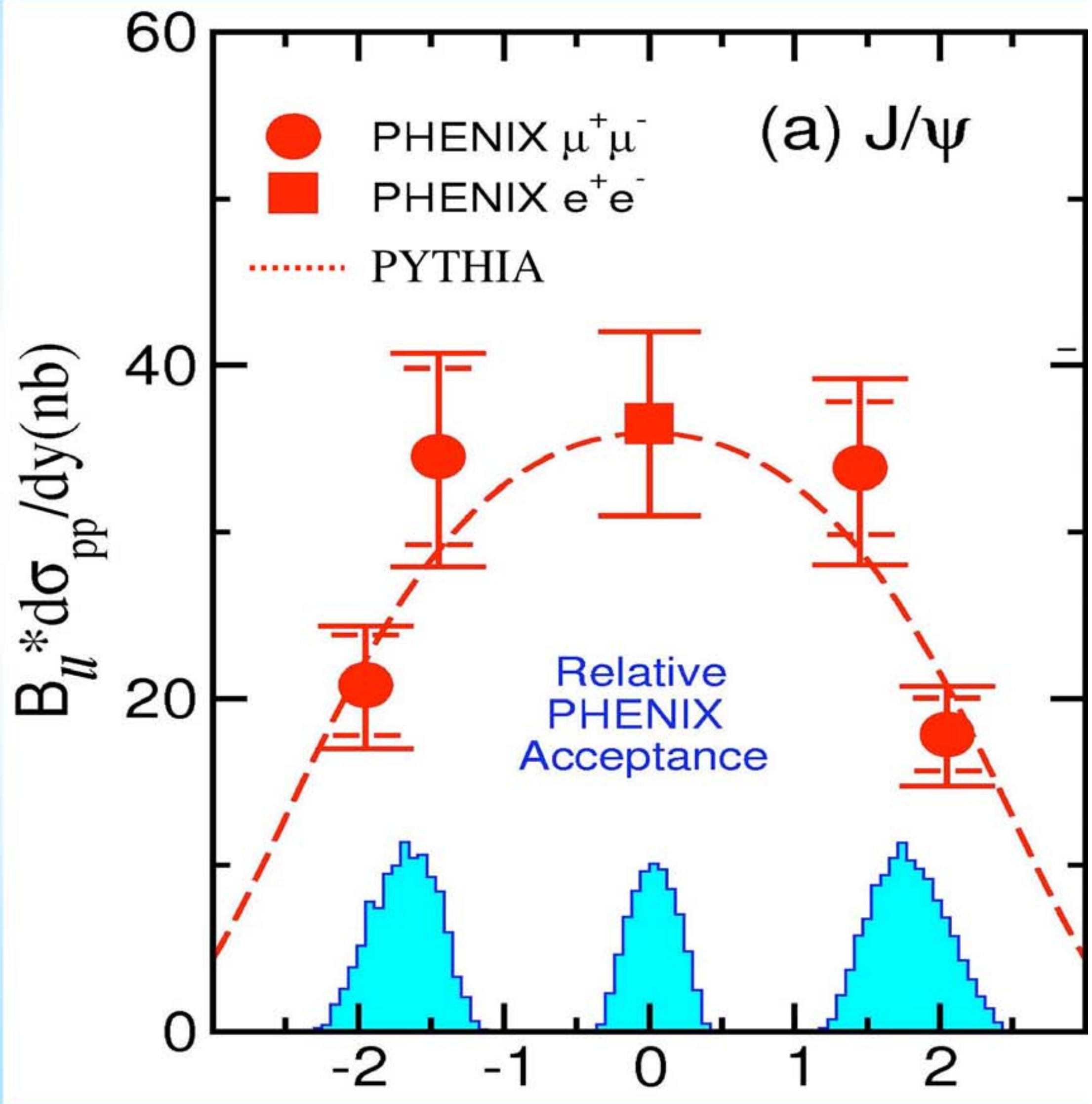
Phys. Rev. Lett. **96**, 012304 (2006).



- Consistent with trend of world's data and with the Color Octet Model calculation

J/ψ Cross Section vs Rapidity

- Good agreement with PYTHIA calculation shape
- Variation in pdf's negligible relative to errors
- x10 higher statistics from run 5
- x30 higher statistics from run 6



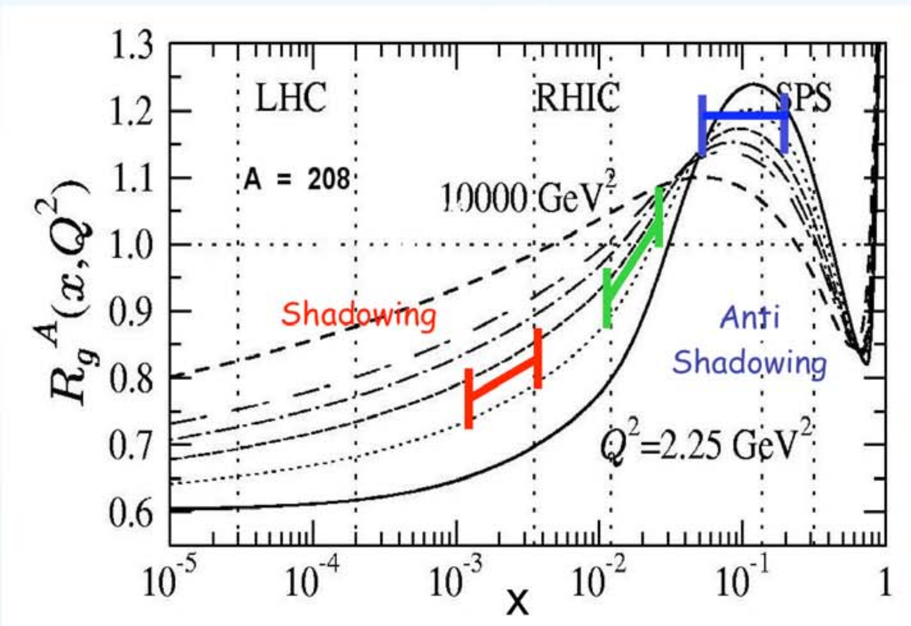
Cold Nuclear Matter - d+Au

- Used to disentangle initial state and nuclear medium effects ⇒ shadowing, anti-shadowing, gluon saturation, nuclear absorption, energy loss, etc.

Cold Nuclear Matter - d+Au

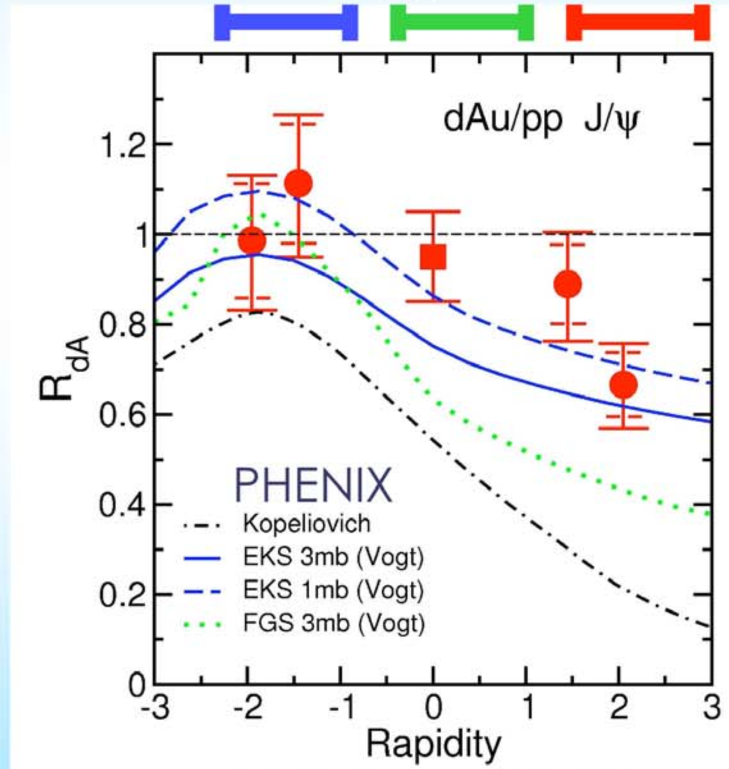
- Absorption of J/ψ by nuclear matter
- Modification of PDF due to gluon shadowing

Models



Nucl. Phys. A696 (2001) 729-746

Data



PHENIX PRL 96, 012304 (2006)

Vogt, PRC71, 054902 (2005), Kopeliovich, NP A696, 669 (2001)

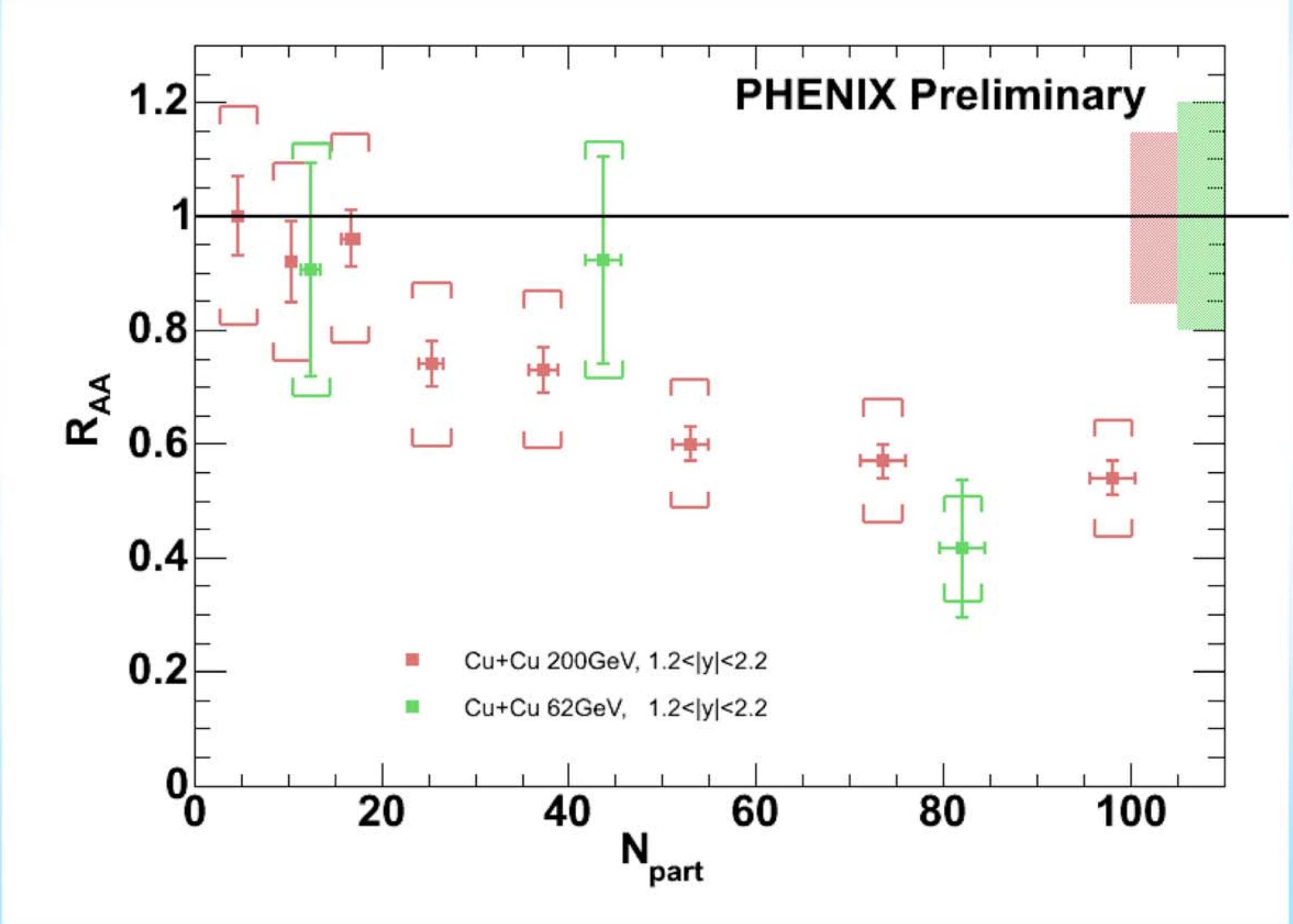
PHENIX data compatible with:
- weak gluon shadowing
- weak absorption : 1 mb (max 3mb)

Heavy Ion Collisions

- Quarkonia act as probe of medium to disentangle competing effects ⇒ Color Screening, Comover Interactions, Recombination, Sequential Dissociation, etc

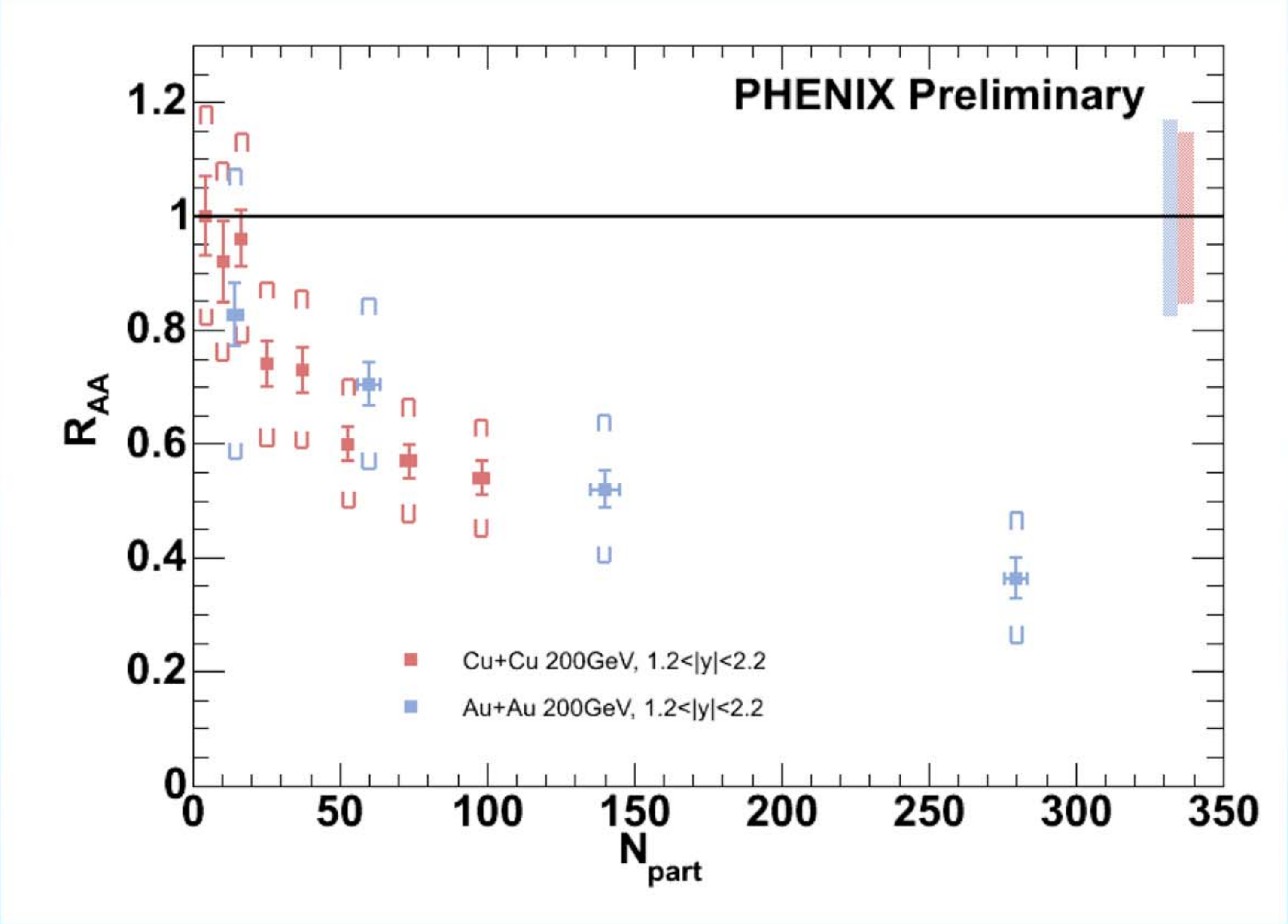
Energy comparison at forward rapidity

Cu+Cu, $\sqrt{s}$ = 200GeV and 62GeV, 1.2 < |y| < 2.2



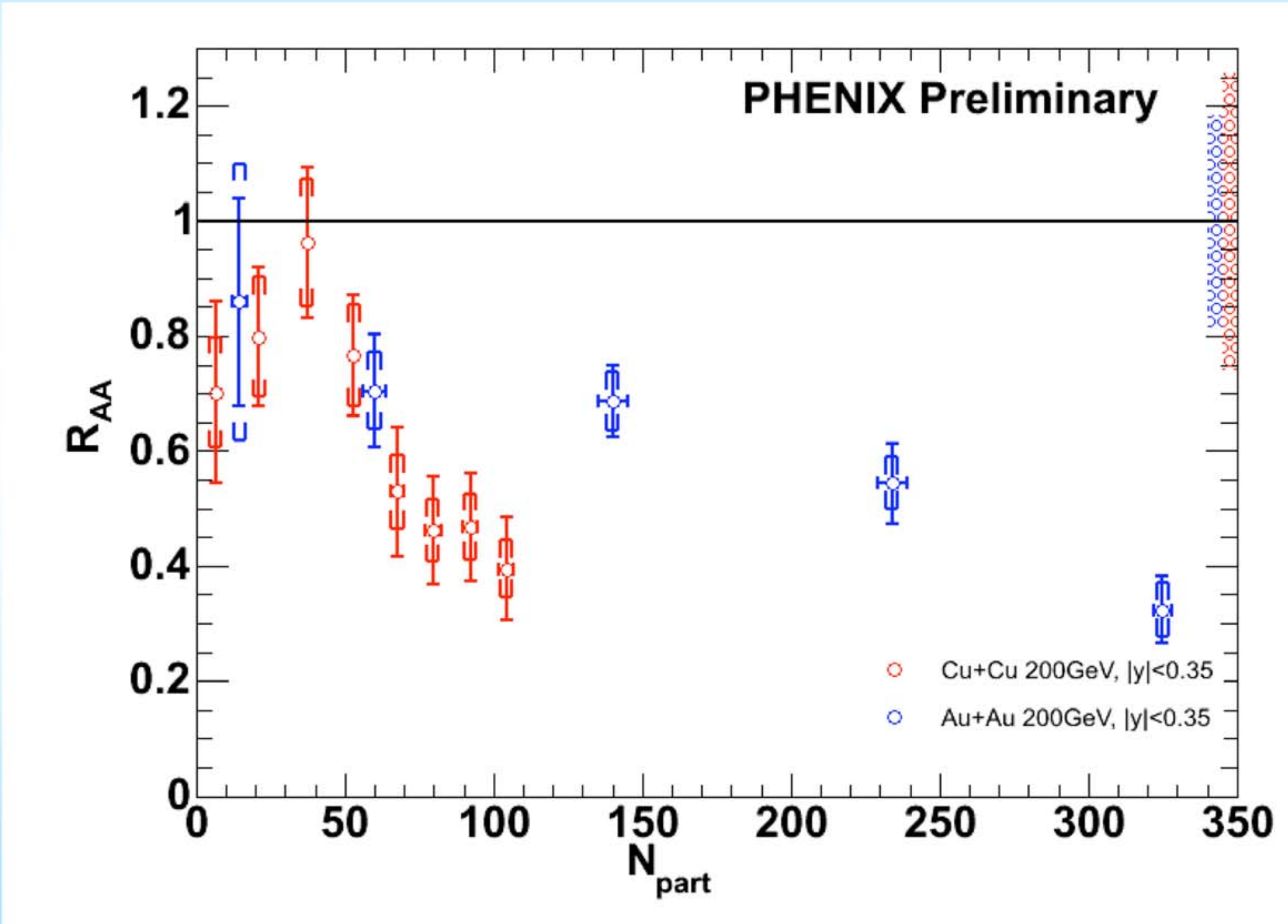
System size comparison at forward rapidity

Au+Au and Cu+Cu, $\sqrt{s}$ = 200GeV, 1.2 < |y| < 2.2



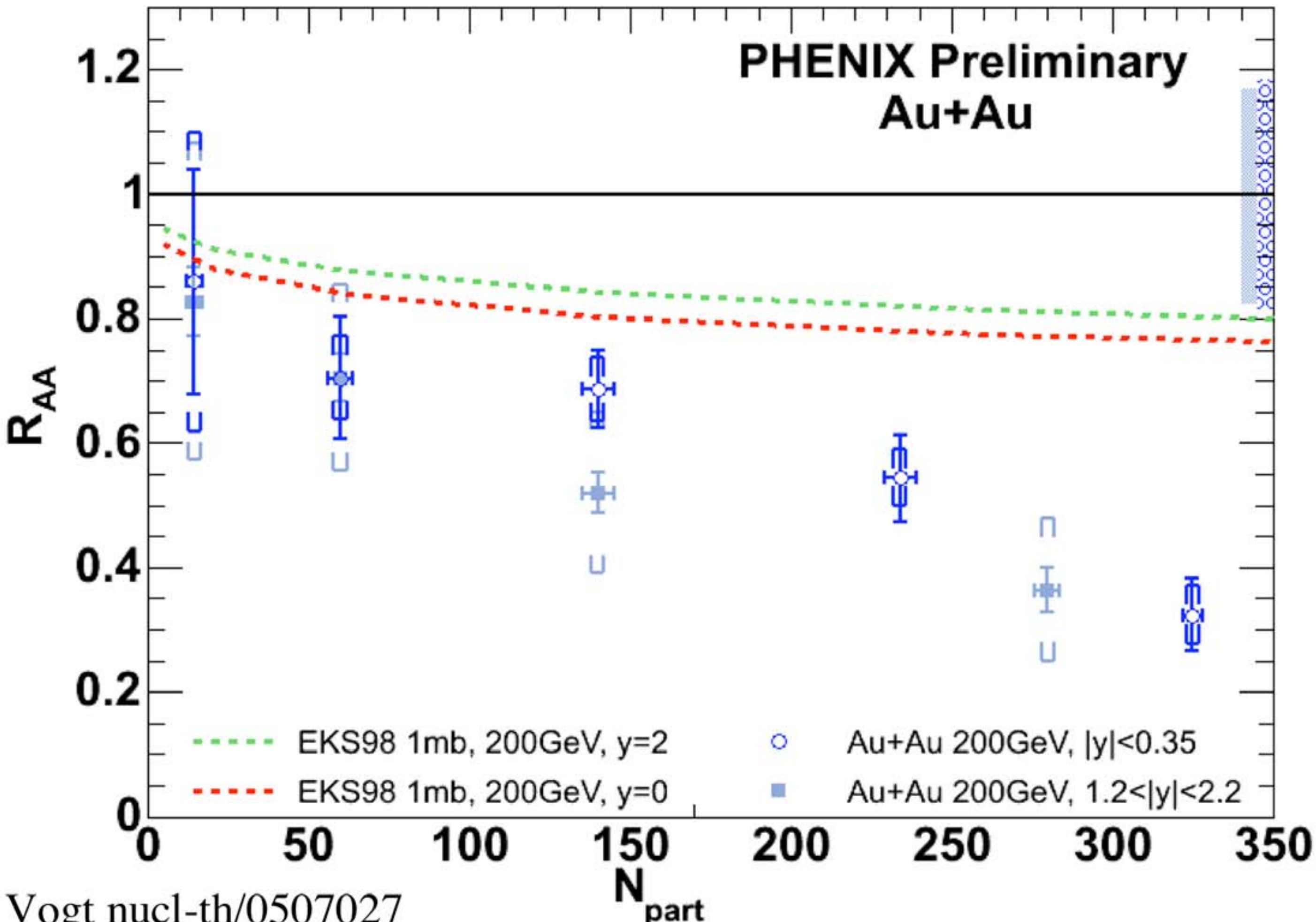
System size comparison at mid rapidity

Au+Au and Cu+Cu, $\sqrt{s}$ = 200GeV, |y| < 0.35



PHENIX Data & CNM Models

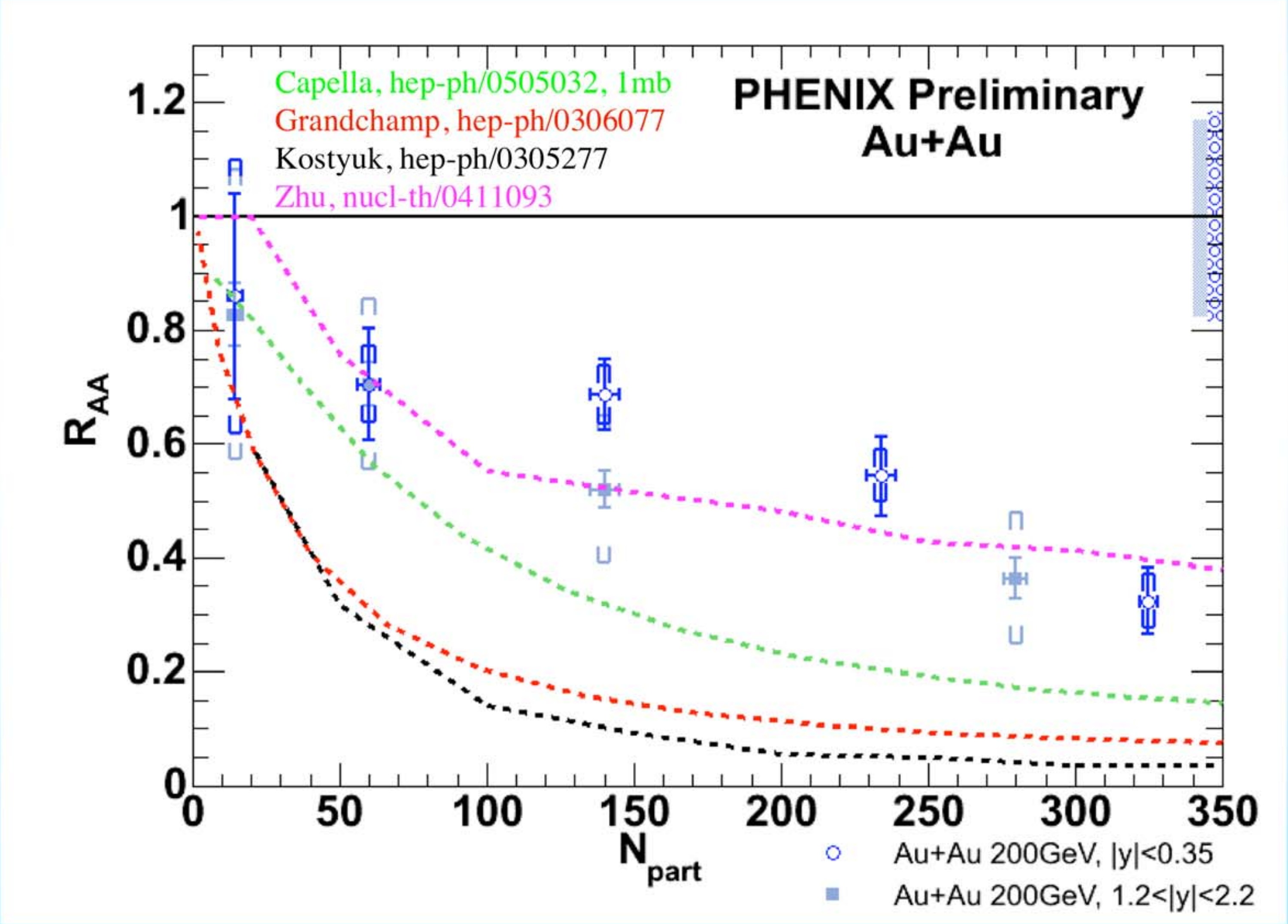
Cold nuclear matter models



R. Vogt nucl-th/0507027

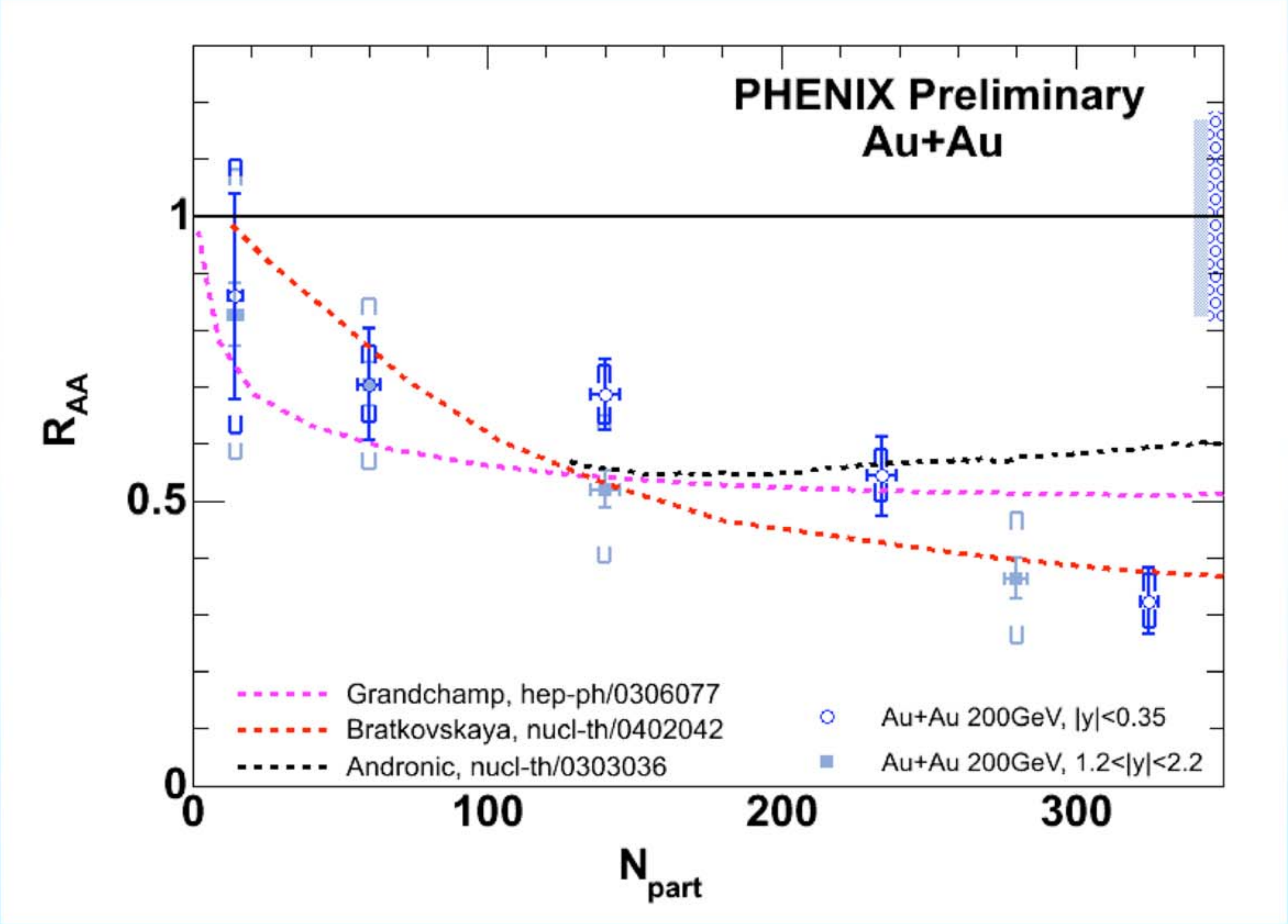
PHENIX Data & Suppression Models

Suppression models w/o regeneration

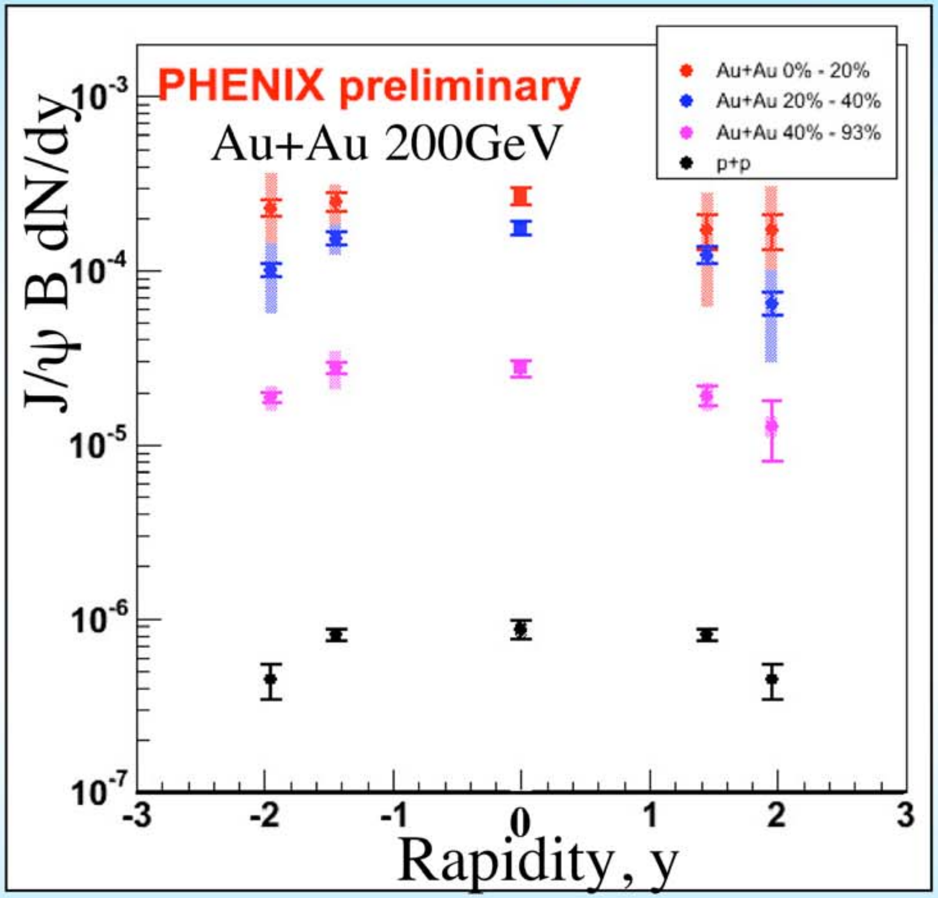


PHENIX Data & Regeneration Models

Suppression models with regeneration



Rapidity Dependence



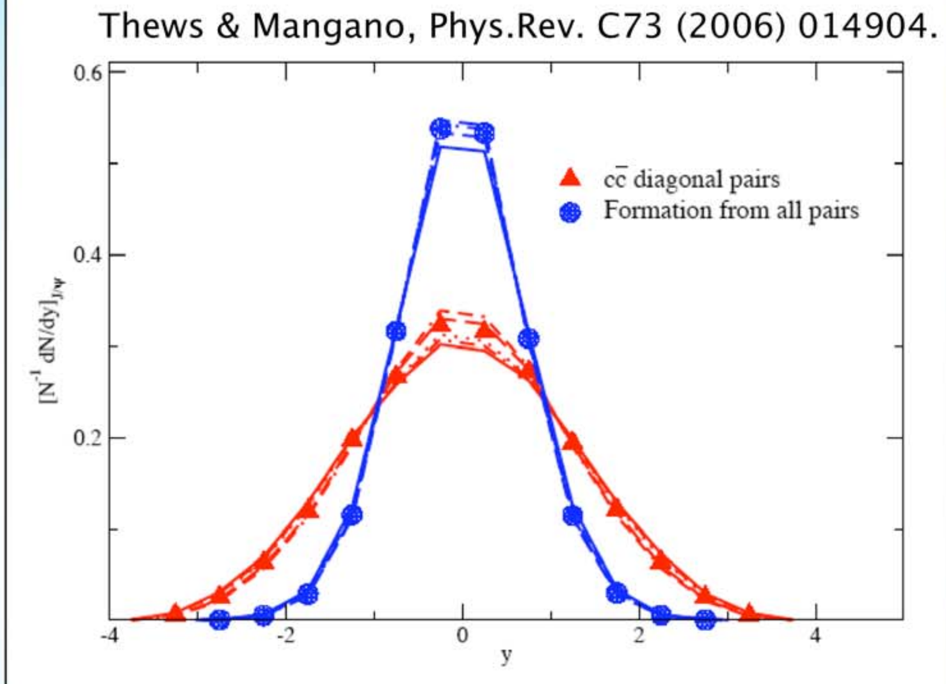
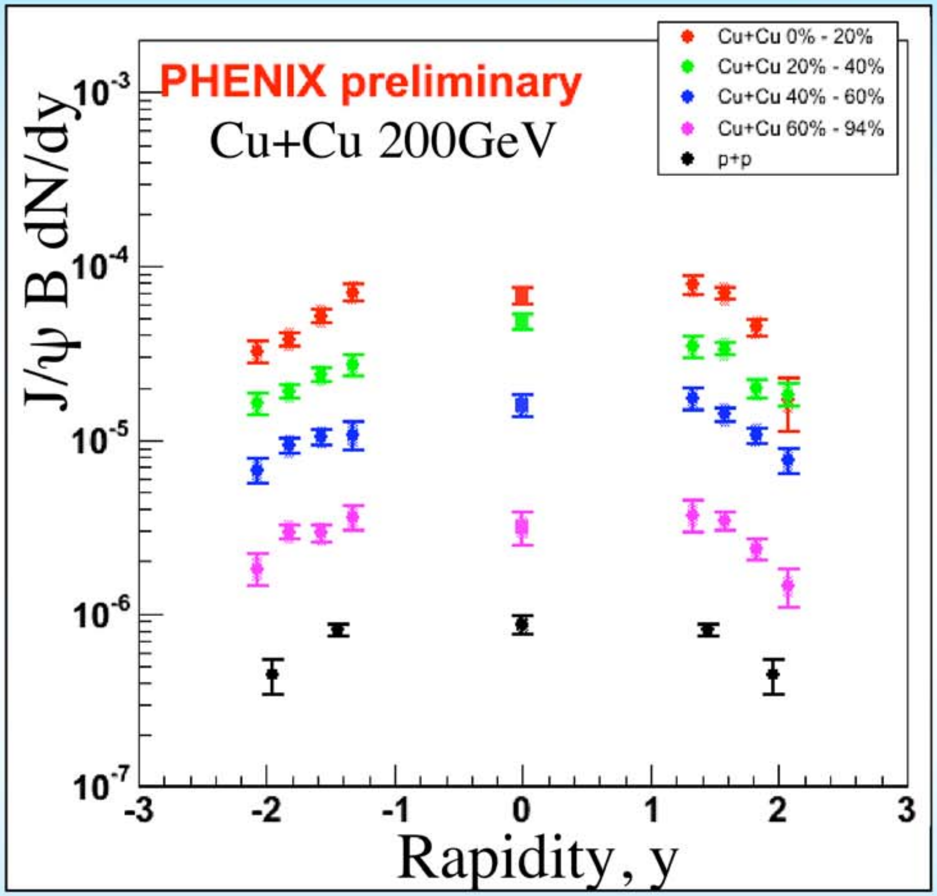
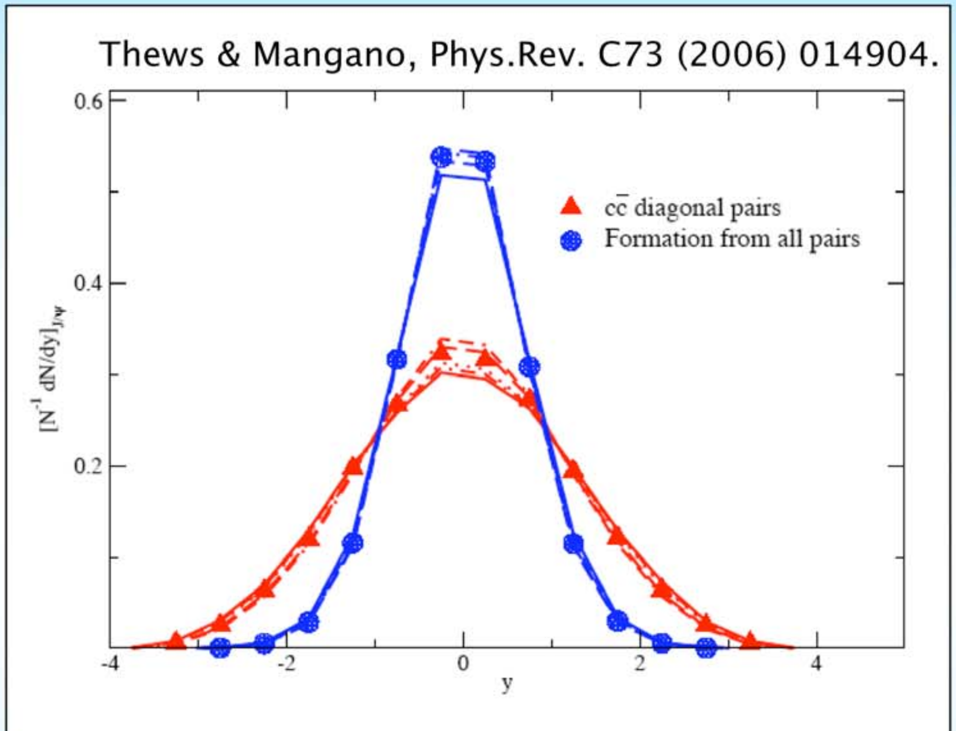


FIG. 21: Predicted rapidity spectra of J/ψ in Au-Au interactions at 200 GeV. Triangles are for initial production via diagonal $c\bar{c}$ pairs. Circles are for in-medium formation via all pairs.

- Shape of rapidity dependence of J/ψ yield consistent as a function of centrality
- No difference observed between Cu+Cu and p+p data distributions at 200GeV within errors
- Rapidity narrowing predicted by recombination models clearly not present

Rapidity Dependence





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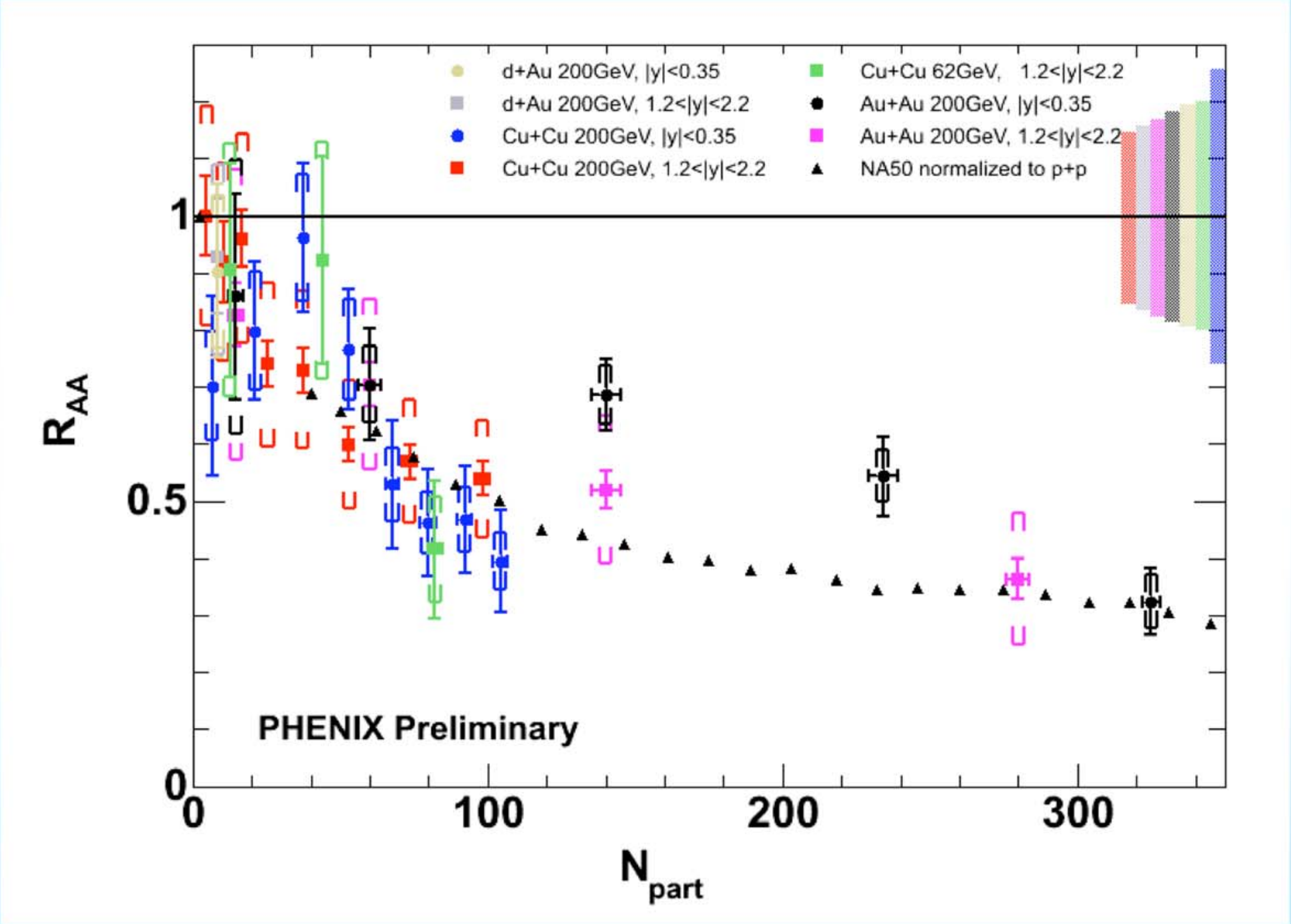
NA50 & PHENIX Comparison

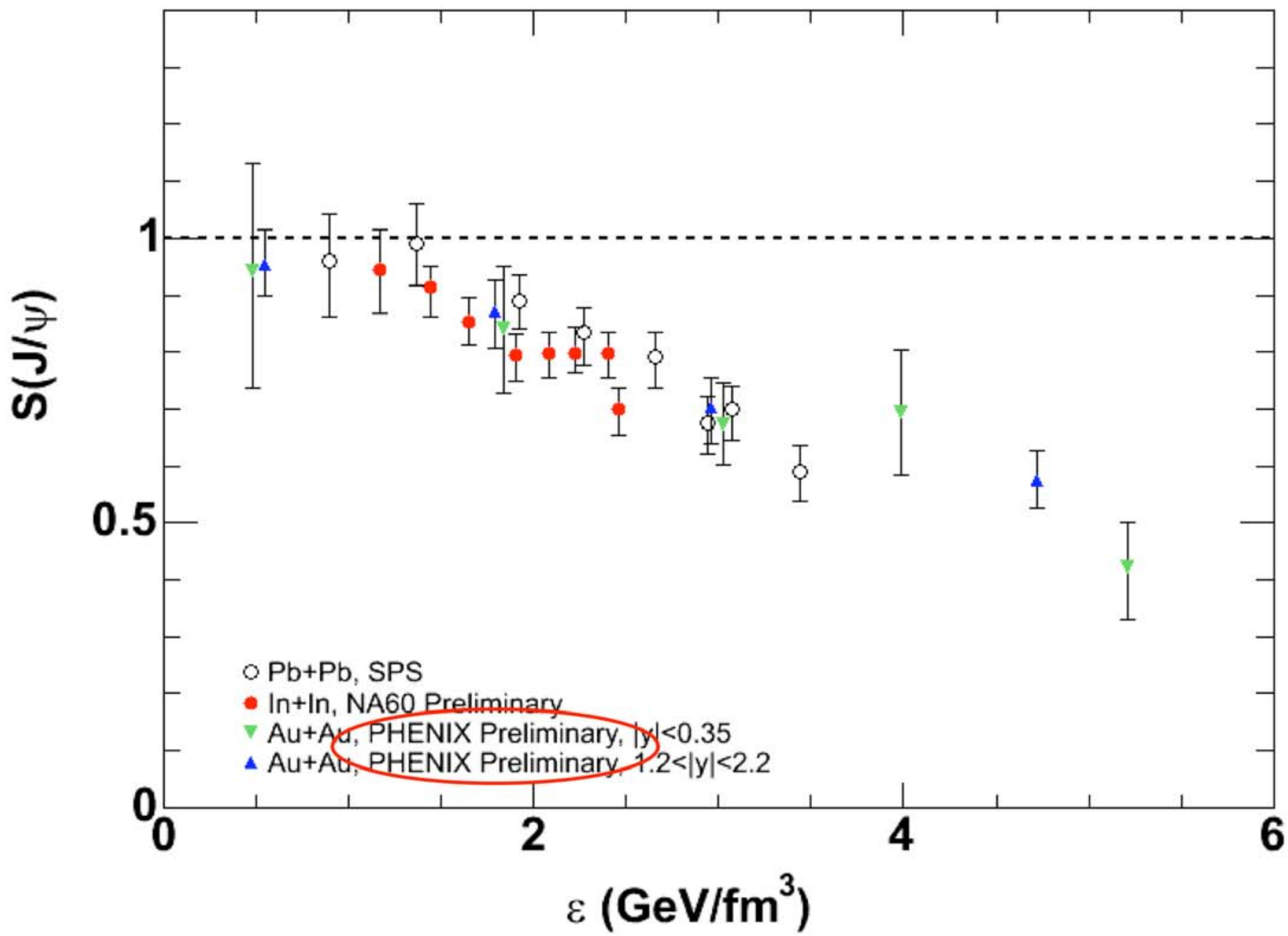


Sequential Dissociation

$$S(J/\psi) = 0.6 S_{\psi} + 0.4 S_{\chi_c,\psi'}$$

survival probability relative to normal nuclear matter

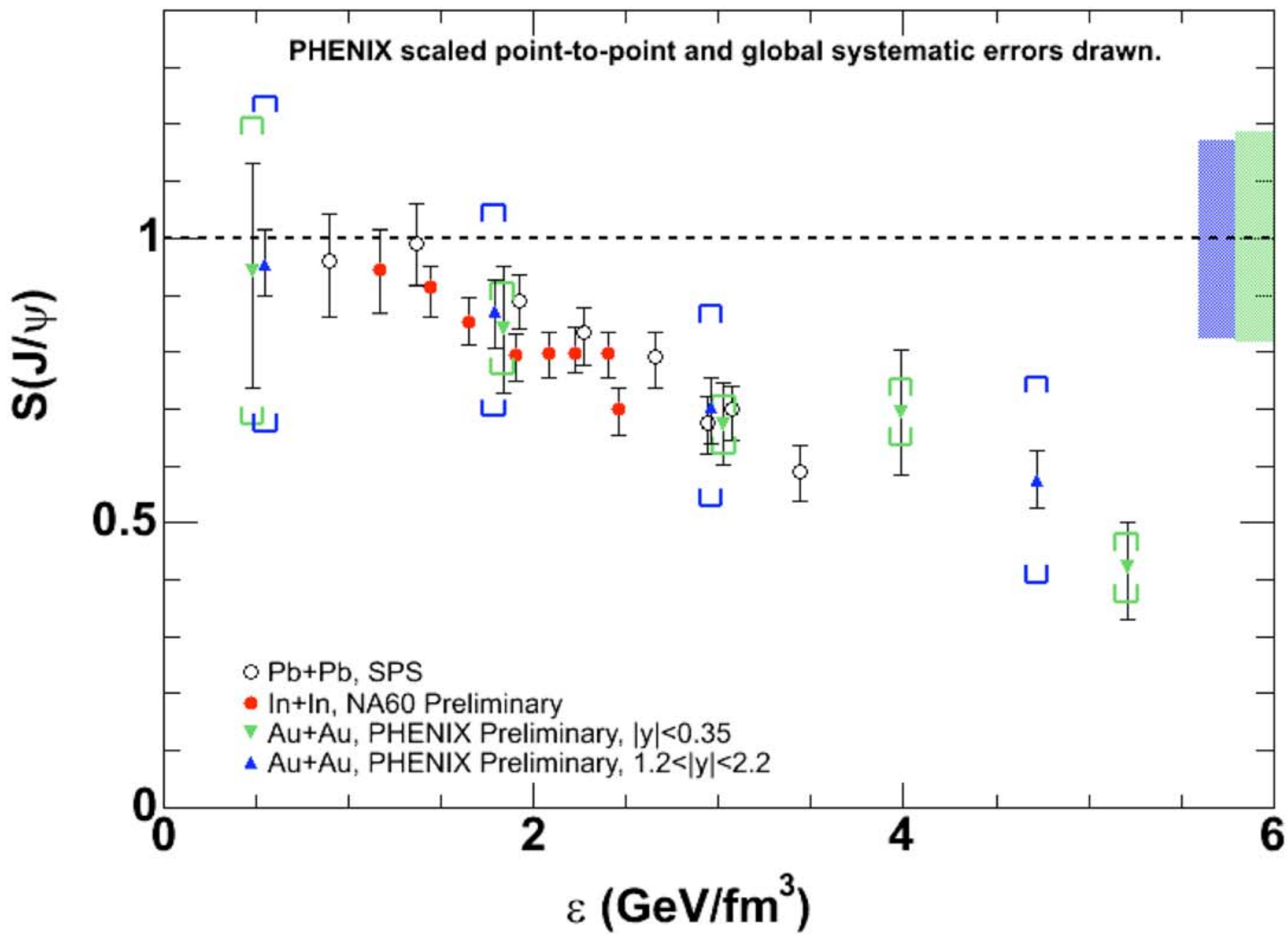
Figure 5: Karsch, Kharzeev & Satz, PLB 637, 75 (2006).



Sequential Dissociation

Show real Au+Au systematic errors - pt-to-pt and global scale
(Note: real systematic errors associated with SPS data exist also!)

Figure 5: Karsch, Kharzeev & Satz, PLB 637, 75 (2006).

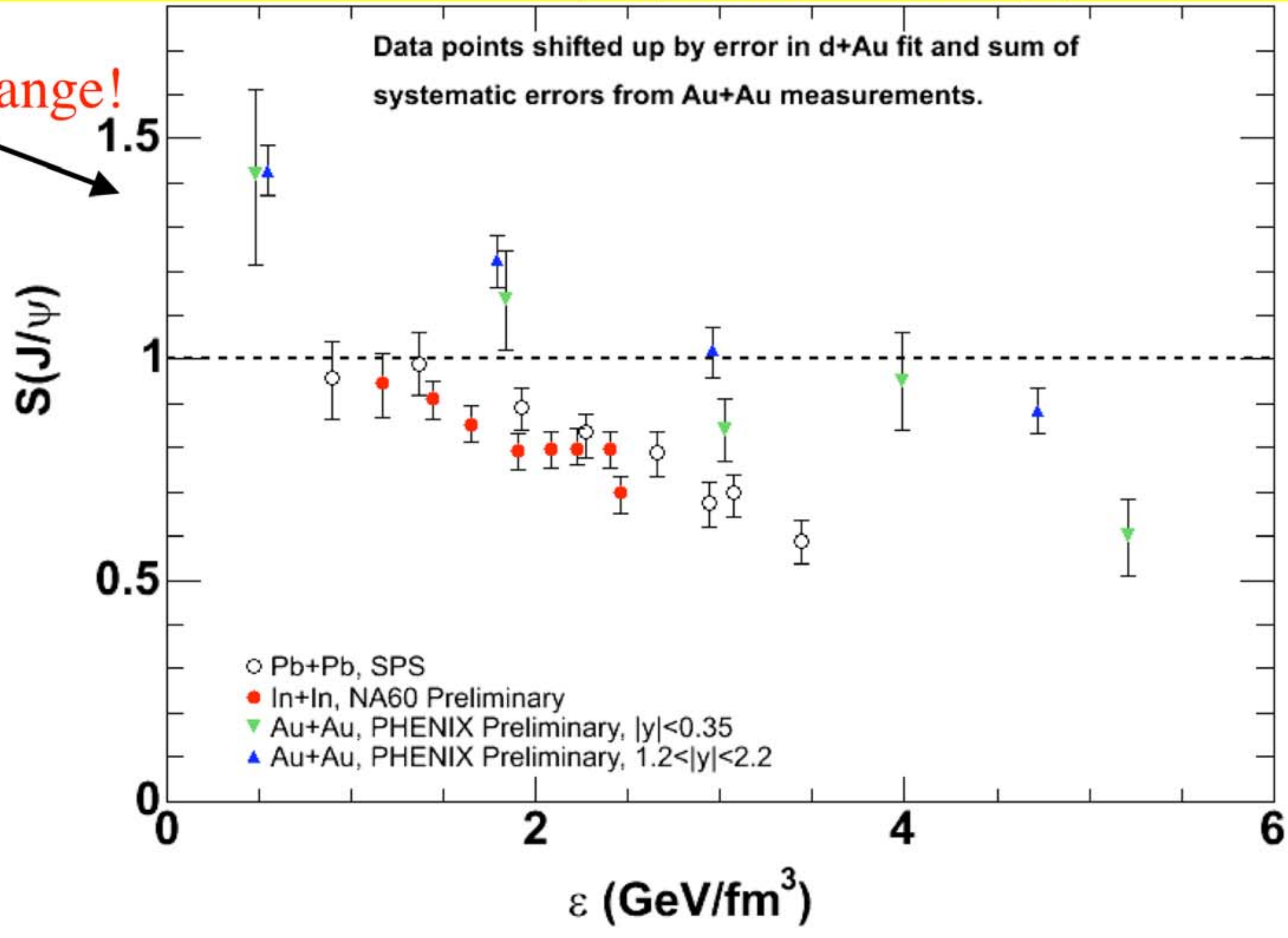


Sequential Dissociation

Shift dAu baseline down and AuAu points up by the systematic

$$S_i^{AA}(y,N_{part}) = \frac{R_{AA}(y,N_{part})}{\exp\left(-n_0\left[\sigma_{diss}(y)+\sigma_{diss}(-y)\right]L\right)}$$

Scale Change!



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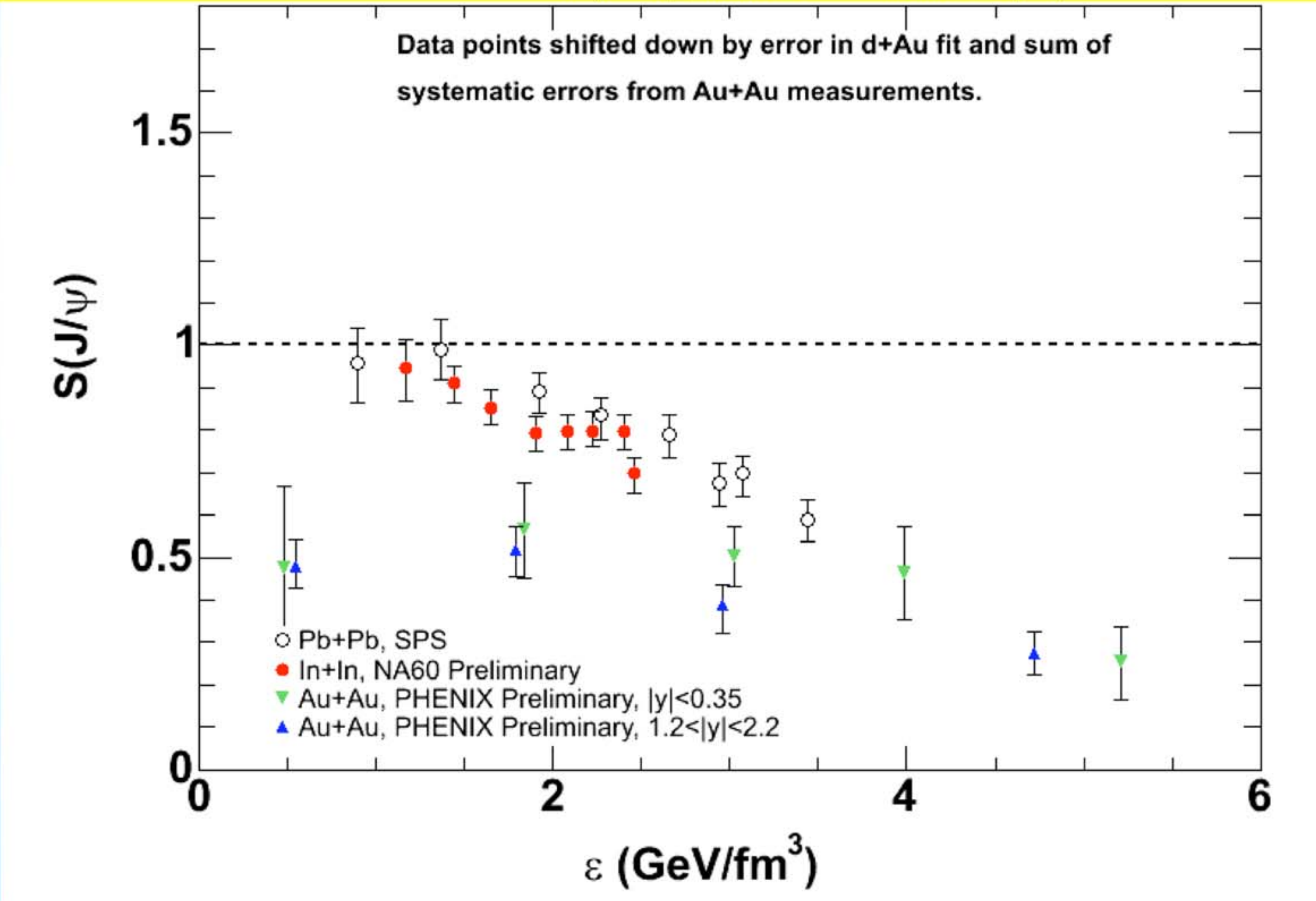
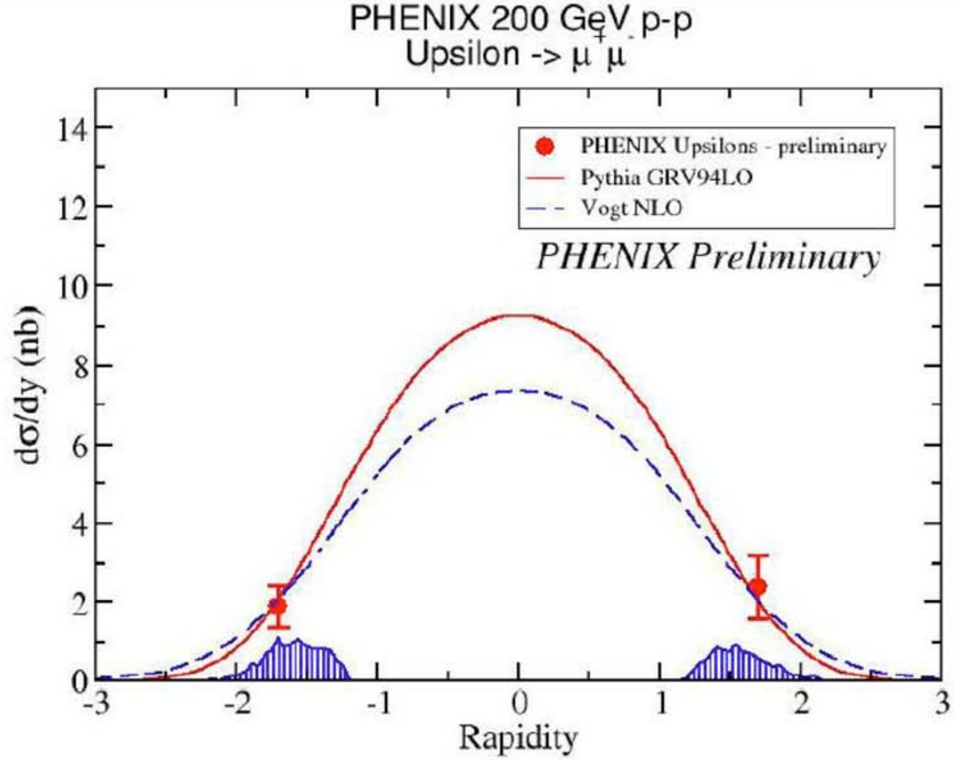
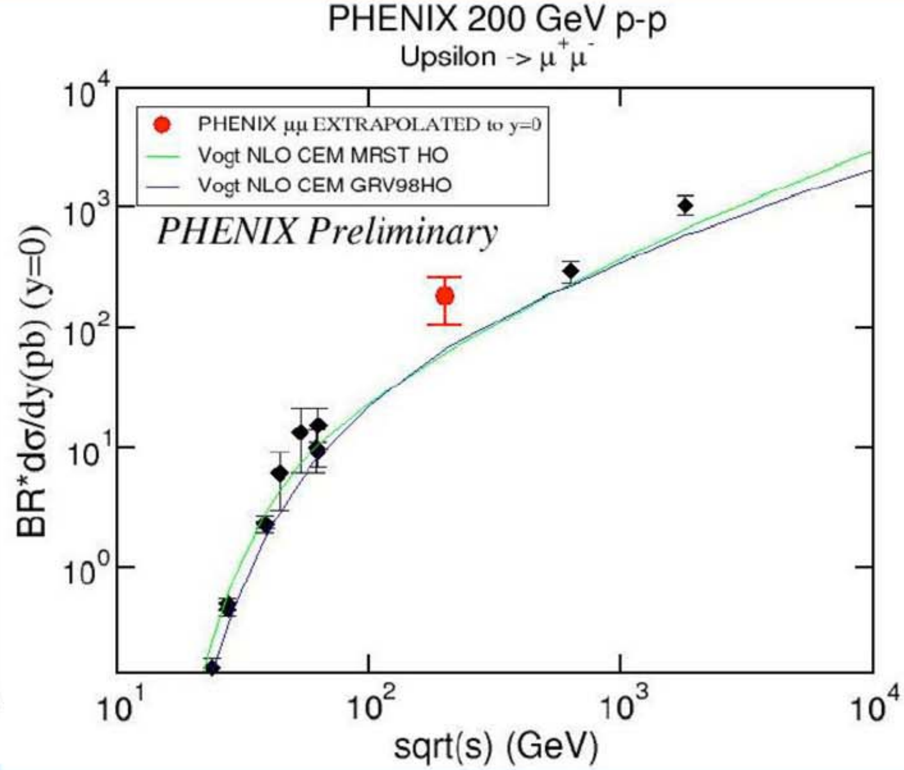


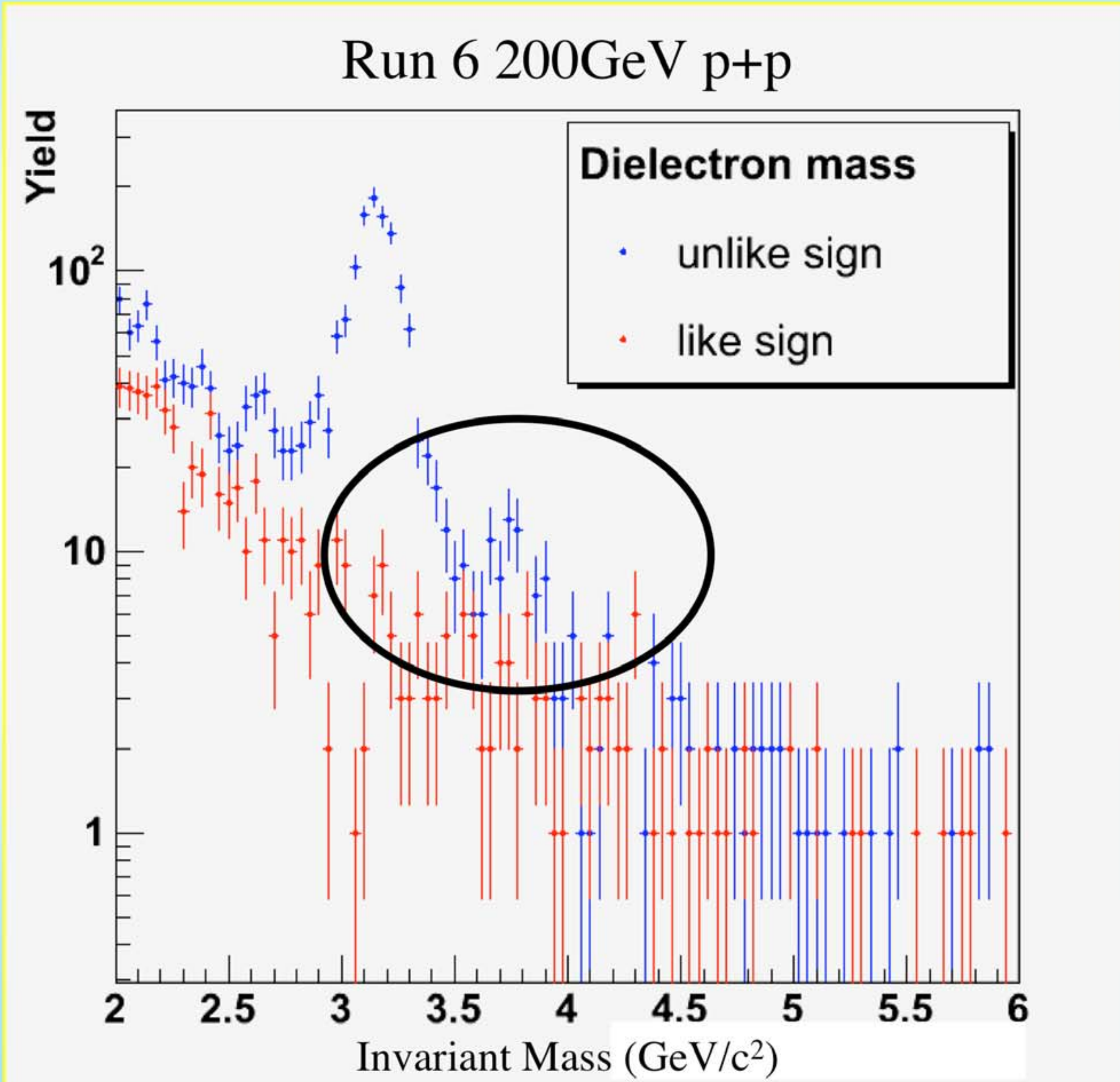
First Upsilon Measurement



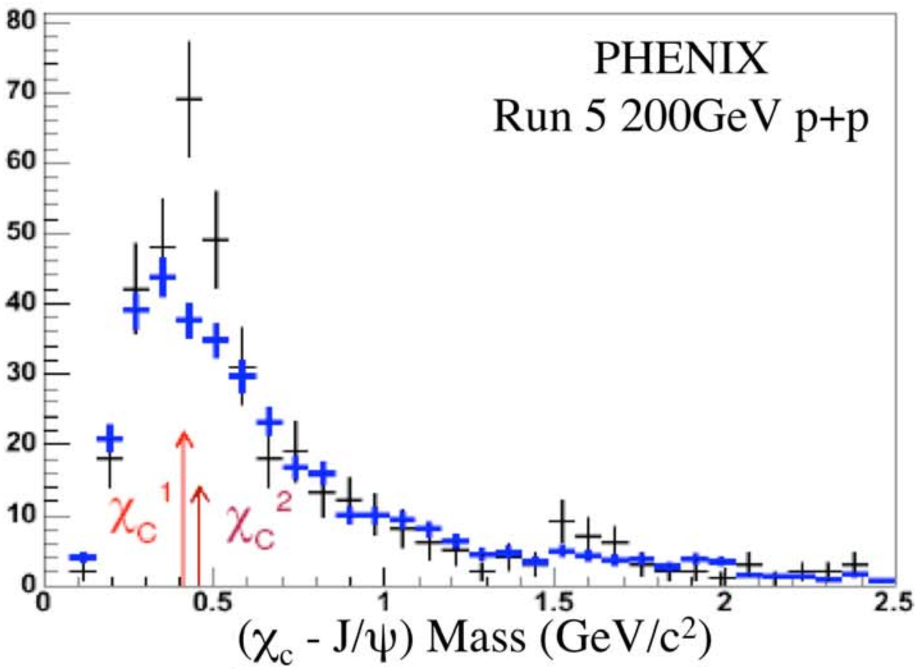


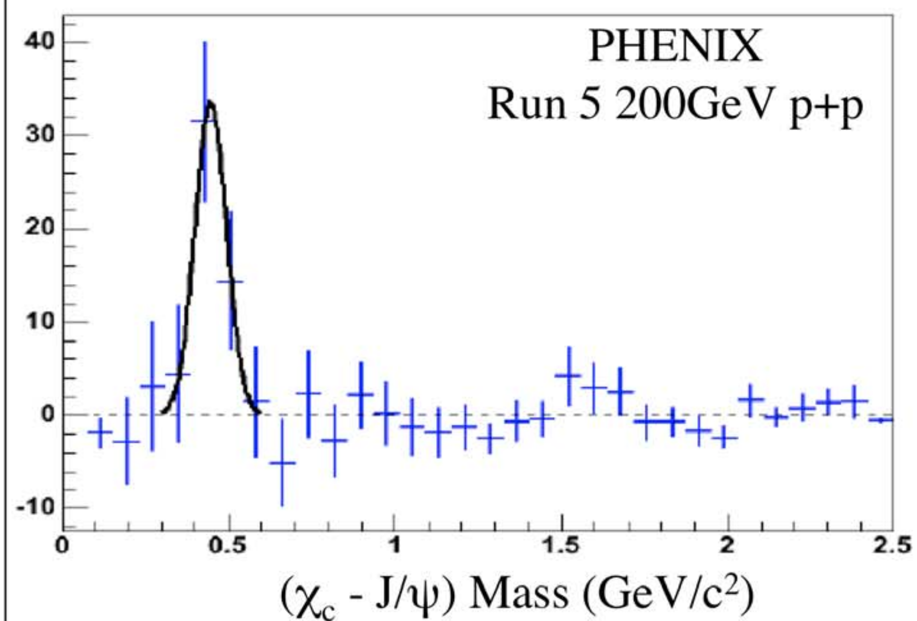
- Signal extraction assumes excess in ϒ mass region is strictly from ϒ's
- Rapidity dependence requires mid-rapidity point to constrain fit
- Preliminary cross section appears consistent with trend in world's data

Future Measurements: ψ'



Future Measurements: χ_c





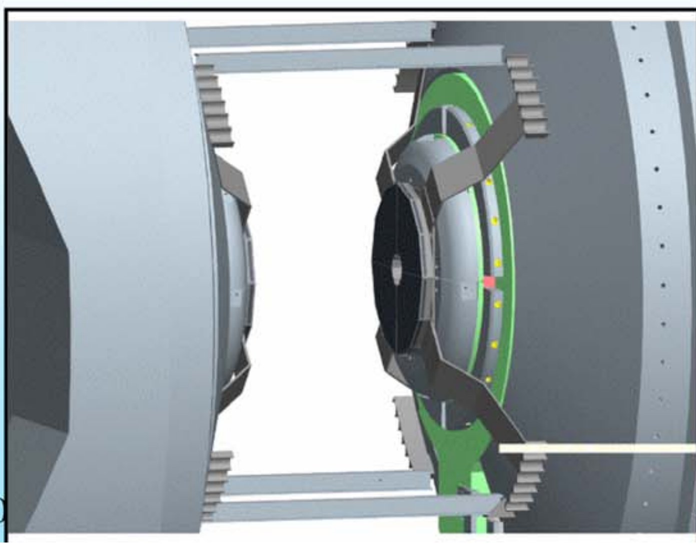
Run 6 data set has a factor of x3 more luminosity

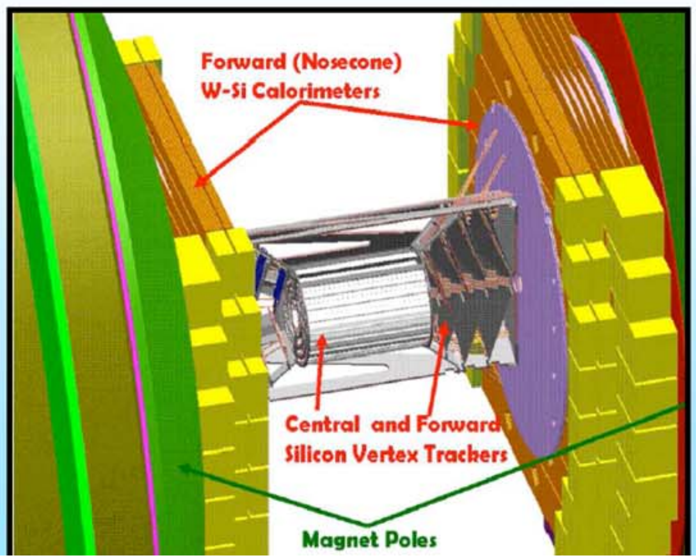
PHENIX Future

* Provided the PAC smiles upon us….
  Run 7: high statistics Au+Au 200GeV, x4 luminosity
  Run 8: high statistics d+Au 200GeV, x10 luminosity

PHENIX Detector Upgrades:
✓Reaction Plane Detector
✓Si Vertex Detector
✓Nosecone Calorimeter

RHIC Upgrades:
✓Increased luminosity
✓Increased species



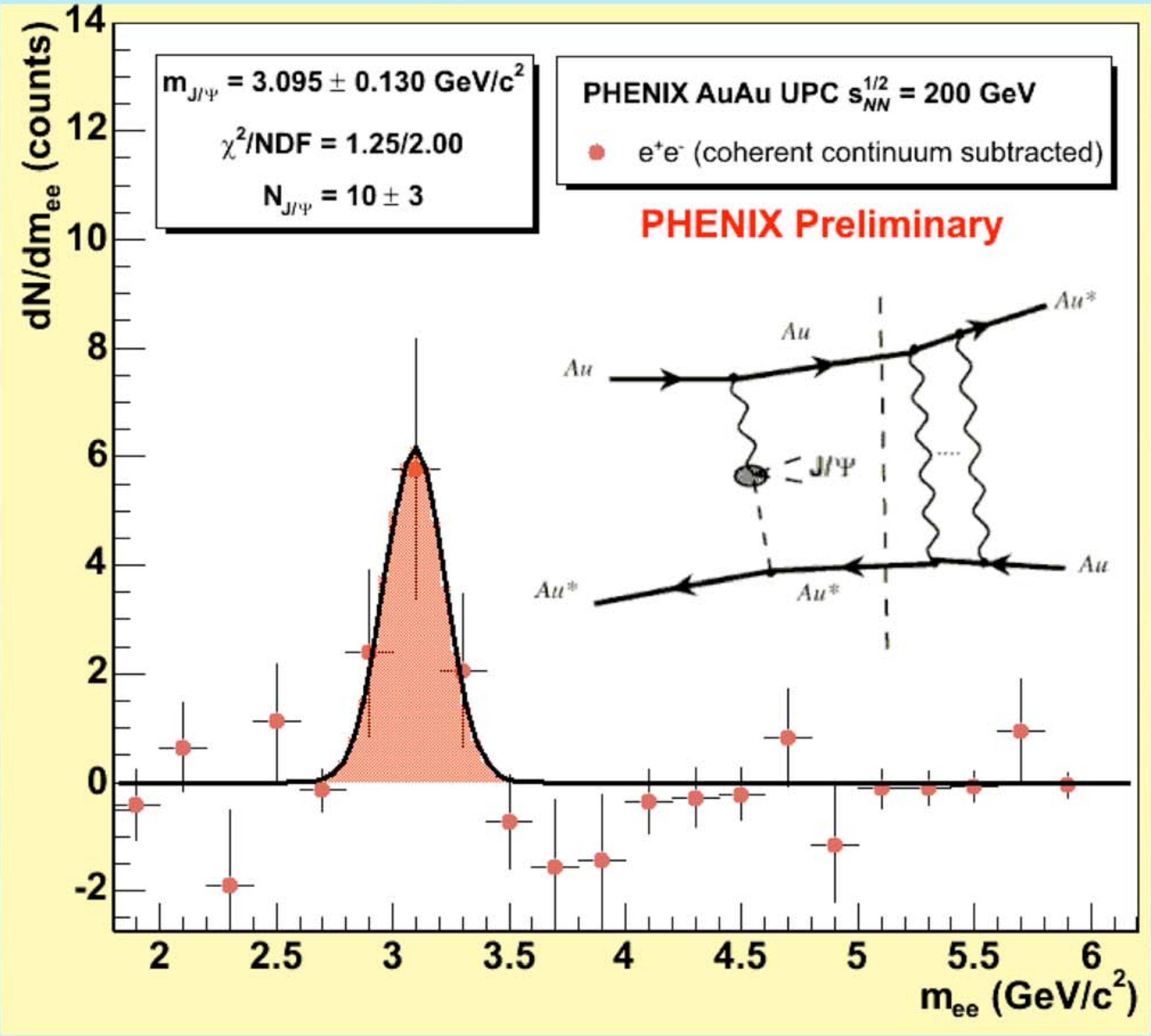


The Tip of the Iceberg

- PHENIX quarkonia results are just beginning….
- Light Ions:
  - p+p data consistent with world's data and provides useful reference baseline
  - d+Au data is beginning to allow cold nuclear matter effects to be disentangled
  - Errors on results will dramatically improve with the analysis of higher statistics data sets
- Heavy Ions:
  - The similarities between the suppression observed at the SPS and RHIC is striking
  - Recombination of uncorrelated quarks?
  - Sequential dissociation of charmonium states?
- Improved measurement of Υ, ψ'and χ_c to come in p+p collisions
- Future PHENIX data will shed light on these processes and open additional exciting avenues of quarkonia measurements

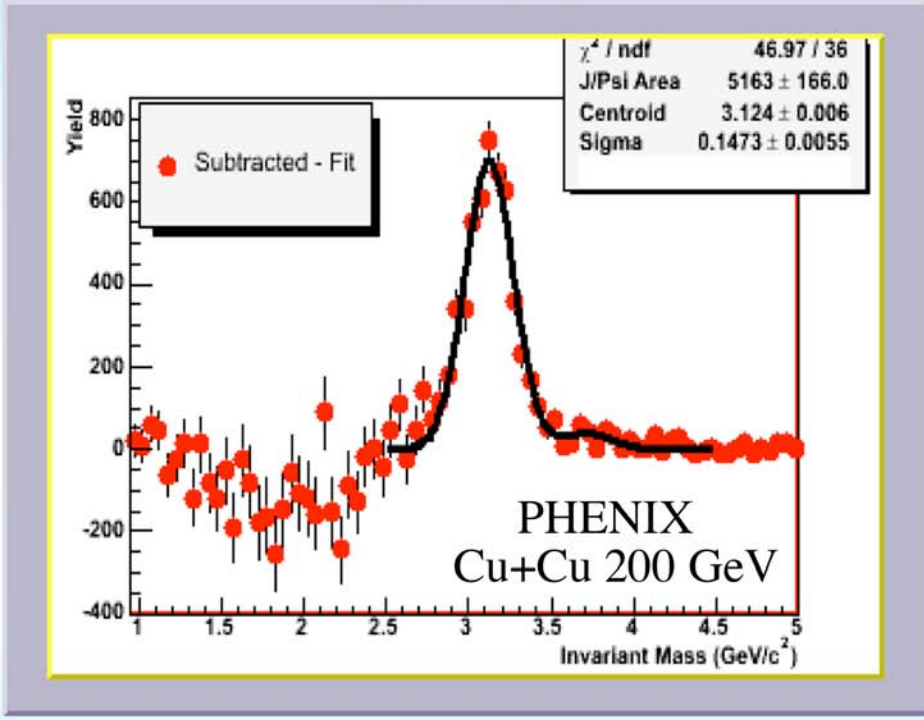
Backup

Ultra-Peripheral Collisions

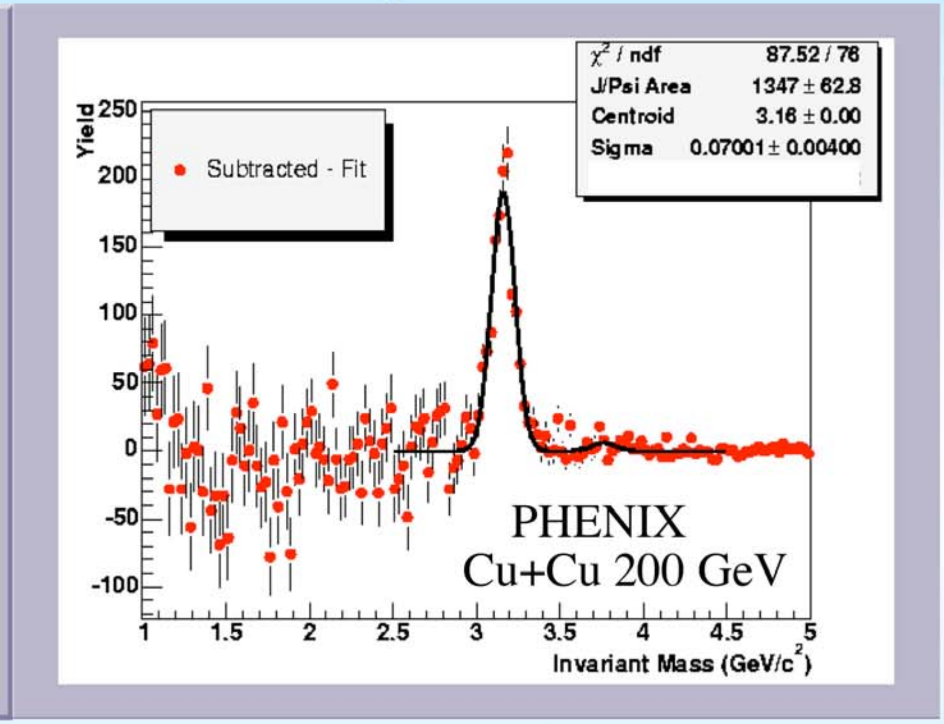


Invariant Mass Plots

$J/\psi \rightarrow \mu^+\mu^-$



$J/\psi \rightarrow e^+e^-$

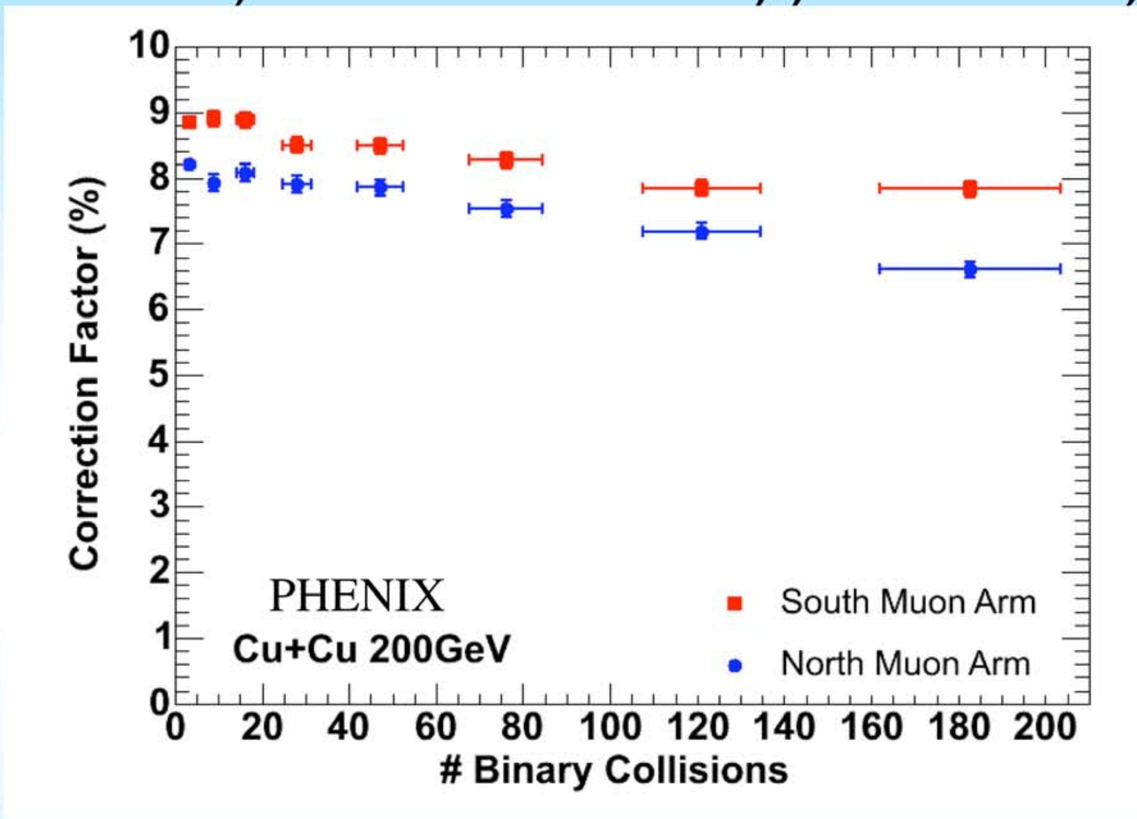


$$N_{J/\psi} = N^{+-} - 2\sqrt{(N^{++} * N^{--})}$$

Like sign subtraction method used to isolate J/ψ signal

Integrate over mass range of 2.6-3.6 GeV/c^2

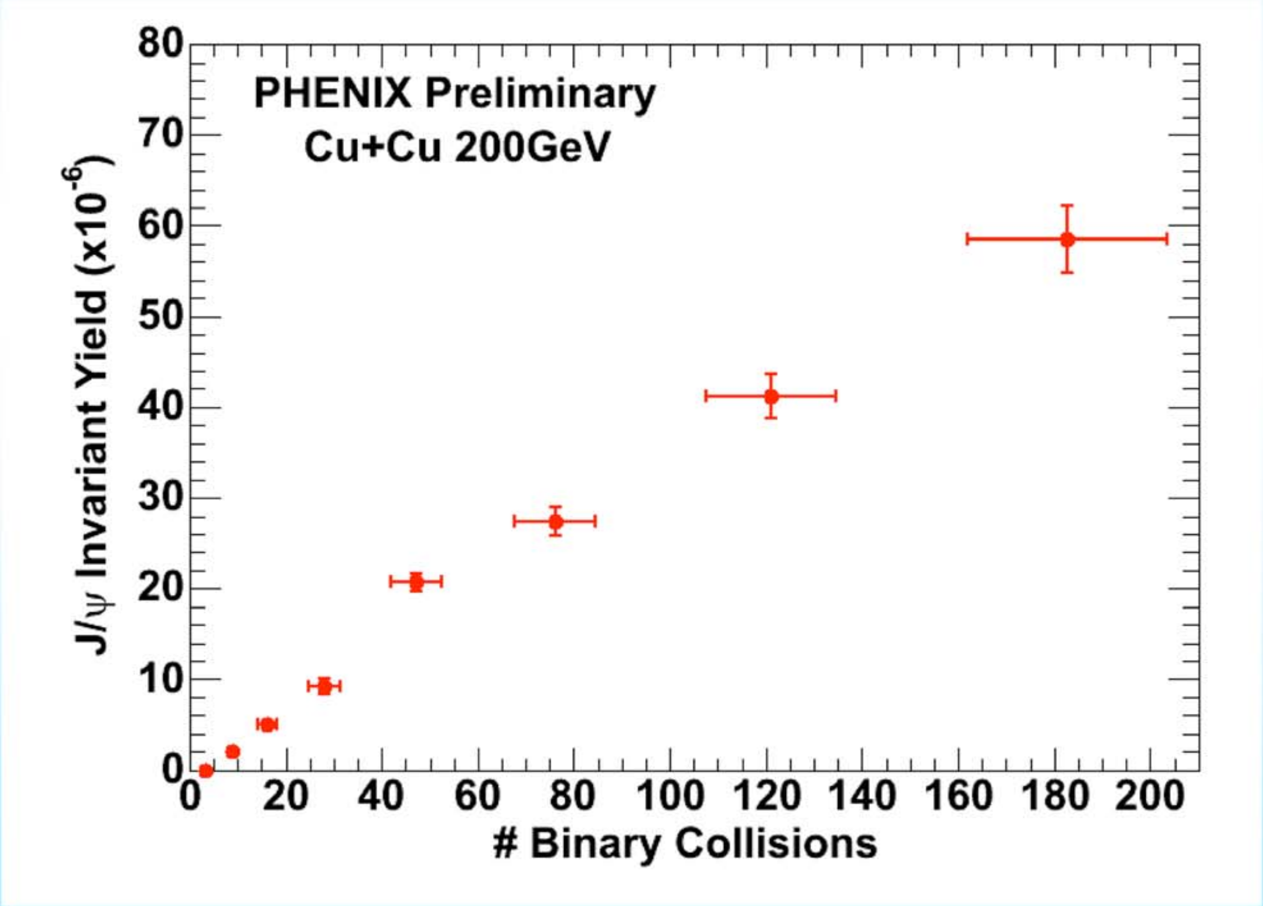
Acceptance * Efficiency



- Detector geometrical coverage
- Detector hardware performance
- Trigger efficiency
- Reconstruction efficiency

J/ψ Invariant Yield

$$B * \frac{dN_{J/\psi}}{dy} = \frac{N_{J/\psi}}{N_{evt} * A\varepsilon}$$



Comparing Systems and Energies

- PHENIX data:
  - Au+Au 200GeV
  - Cu+Cu 200GeV
  - Cu+Cu 62GeV
  - p+p 200GeV
  - d+Au 200GeV

$$R_{AA} = \frac{1}{N_{coll}} \frac{\left(B * {dN_{J/\psi}}\big/{dy}\right)_{AA}}{\left(B * {dN_{J/\psi}}\big/{dy}\right)_{pp}}$$

- Nuclear Modification Factor (R_{AA}):
  - Scale measured invariant yield by invariant yield found in p+p collisions at the same energy
  - Account for differing number of nucleons by scaling by the number of binary collisions